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REVIEW ARTICLE

Rhizosphere borne beneficial microbes for promoting plant growth in calcareous and sodic soils– An overview

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Abstract

Sodic and calcareous soils are characterized by high sodium and calcium carbonate content. Excess sodium in sodic soils leads to surface crusting and dispersion of clay particles. The presence of calcium carbonate in calcareous soil results in higher soil pH, poor soil structure, low phosphorus availability and low fertility, all of which significantly reduce crop productivity. Effective management of these soils is highly essential for improving soil fertility and ensuring crop productivity, particularly in India, as 6.73 M ha of land are salt affected, whereas 229 M ha are calcareous. Bio-augmenting this problem soil with salt-tolerant beneficial microorganisms has emerged as a promising strategy for addressing these issues. Salt-tolerant bacteria can withstand salt concentrations up to 30 % by accumulating ideal solutes for osmoregulation, producing extracellular proteases and stimulating Na^{+}/ H^{+} antiporters. These beneficial microorganisms can improve soil structure, increase nutrient availability, promote the leaching of excess salts and solubilize calcium carbonate by producing organic acids. Salt-tolerant plant growth-promoting bacteria could alleviate stress in plants through various mechanisms and this review paper provides an overview of salt-affected soils and the importance of rhizosphere-borne microbes in alleviating salt stress. Integration of microbial strains with traditional soil amendments provides an eco-friendly and effective approach for restoring soil health and promoting sustainable agriculture in sodic and calcareous soils.

Keywords: calcareous soil; characterization; constraints; distribution; reclamation; sodic soil

Introduction

Soil serves as a basis for land biomes, with varying soil characteristics resulting from the interaction of several soil-forming elements such as climate, organisms, topography, parent material and time (1). It acts as a resource to provide both essential macro and micronutrients needed for crop growth (2). Soil health is an innate property of soil that plays a key role in sustainable farming (3) and it can be sustained and managed through various amendments and management practices. Soil health determines the choice of crop and influences crop growth (4). In recent years, many soils around the world have become unsuitable for crop cultivation (5) due to deteriorated soil health (6), caused by factors such as soil compaction, salinization, acidification and sodification. Apart from these, the incorporation of synthetic chemicals and heavy metals also contributes to the degradation of soil characteristics (7, 8) and the decline of soil health, which leads to the development of degraded soils. Soils that are unsuitable for crop production without the adoption of specific management practices are known as problem soils (9). Problematic soils are formed due to improper agricultural practices and human-induced pollution (4). These soils are categorized into (i) physical, (ii) chemical, (iii) biological and (iv) nutritional problem soils (10). Chemically affected soils are more challenging among the problematic soils (9).

Areas under salt-affected soils are continuously increasing around the world due to improper land use and management practices leading to a decline in soil health and reduced sustainability of crop production (11). Salt-affected soils are developed through various processes therefore, they exhibit salinity, sodicity, alkalinity, or a combination of these characteristics (11). The presence of sodium, potassium, magnesium, calcium, chlorides, carbonates and bicarbonate ions causes salinity or alkalinity in soil (10). Accumulation of salts, either in the root portion or on the soil surface, alters the soil properties, characteristics and fertility and negatively affects the physiological processes of the soil (12). Salt imbalance in soil, accompanied with other degradation factors such as soil compaction, wind erosion, water erosion and various types of pollution, leads to land degradation (11). Salt-affected soils require proper management practices to support optimal crop growth (9). Reclamation of salt-affected soil through organic matter application and crop rotation has proven effective in improving crop resistance to salt-affected soils. However, the management of soil with microbes can be a novel and promising approach to addressing the problems caused by salt-affected soils (11). Salt-tolerant plant growth-promoting bacteria alleviates plant stress through various mechanisms. This review highlights salt-affected soils and the role of rhizosphere-borne microbes in alleviating salt stress.

Distribution of calcareous and sodic soils in India

Both sodic and calcareous soils are predominant in arid and semi-arid regions (13, 14). One-third of the world's land surface is occupied by calcareous soil (13) and spreads across 228.8 million hectares of soil in India (15). Calcareous soils are abundant in the states of Maharashtra, Gujarat, Karnataka, Madhya Pradesh, Andhra Pradesh and Tamil Nadu (16) (Fig. 1). Sodic soil covers an area of 37.71 lakh hectares in India (17). The impact of sodicity is significant in eleven states, which together accounts for 80 % of the country's total sodicity area (Fig. 1). It also predominant in the six districts of Tamil Nadu. In India, sodicity represents 35.75 % of Uttar Pradesh, 14.36 % of Gujarat, 11.21 % of Maharashtra, 9.41 % of Tamil Nadu, 4.86 % of Haryana and 4.02 % of Punjab (18). In Tamil Nadu, alkali soils are classified based on sodicity levels as mild (59 %), moderate (32 %) and high (4 %). Districts with high level of sodicity includes Ramanathapuram, Cuddalore, Kanchipuram, Tirunelveli, Thanjavur, Pudukottai, Madurai and Tiruchirapalli (19).

Characteristics of calcareous and sodic soils

Calcareous soil comes under the category of alkaline soils, which are recognized as one of the major types of problem soils (20). Calcium (Ca) and bicarbonate (HCO_3^-) salts are found to be abundant in calcareous soil (20). Calcareous soils generally exhibit a pH above 7 and with excess free calcium carbonate, it rises to 8.5 (13). Calcareous soil is often dominated by free lime and contains substantial amounts of iron (Fe), aluminum (Al) and manganese (Mn). These elements may occur in the form of distinct minerals, as coatings on soil particles, or in complex forms bound to soil organic matter (13). Calcareous soil typically contains lower levels of available nitrogen and organic matter. Due to its higher pH, phosphate gets precipitated as calcium phosphate (such as apatite), thereby reducing the availability of micronutrients such as zinc and iron in the soil (21).

The presence of exchangeable cations such as Na and Mg makes the calcareous soil different from other alkaline soils (22). Calcareous soils contain more than 15 % calcium carbonate ($CaCO_3$), which may occur in different forms, such as powder, nodules, crusts etc. (23). In some calcareous soils, $CaCO_3$ accumulates as a strong, dense layer known as caliche, which restricts the penetration of water and plant roots (13), thereby affecting crop production.

Sodic soil is characterized by a high exchangeable sodium percentage (ESP) above 15, a sodium adsorption ratio (SAR) greater than 13 and a pH between 8.5 to 10. Intensive farming and excessive use of agrochemicals have led to a continuous increase in sodic soil area (15). Under natural conditions, excess sodium is absorbed onto negatively charged clay particles, weakening the force that binds them together. Under wet conditions, sodic soil swells, resulting in dispersion of clay particles from the larger soil mass (24). On drying, these clay particles settle down in the form of dense layers, blocking the soil pores. This weakens the aggregation of soil, leading to structural collapse and plugging off soil pores, which restricts water and air movement through sodic soils (25). In sodic soil, elevation of pH and lower organic matter reduces the transformation of unavailable form of calcium phosphate into the available form (26). The development of sodic soils occurs at three different stages: salt accumulation, salinization and alkalization (27). The presence of higher salt concentrations constraints crop cultivation in calcareous and sodic soils.

Constraints of crop cultivation in calcareous and sodic soils

Higher amount of $CaCO_3$ in calcareous soil affects soil properties, leading to elevated pH, low cation exchange capacity (CEC), low availability of phosphorous, iron, manganese, zinc and copper, loss of nutrients through deep percolation, low organic matter and nutritional imbalance between elements such as potassium, magnesium and calcium. Covering around 30 % of soils worldwide, calcareous soil restricts crop cultivation and reduces crop productivity (28). Physical constraints include surface crusting and impermeable subsurface layers, which hinder nutrient transport and root development, thereby affecting crop productivity (29). Chemical constraints include the unavailability of essential nutrients and micronutrients to plants as these nutrients are present either in immobilized or bound form which would hinder crop production (28). The availability of phosphorus in calcareous soil is low due to its transformation into calcium phosphate (30). The limited availability of micronutrients like iron, zinc and copper poses severe threat to crop growth (31). The emergence of seedlings is often hindered in calcareous soil due to soil crust formation (32). Calcareous soil could be made productive by effective management practices (22).

Soil sodicity has an adverse effect on the physical properties of soil, leading to constrains in soil aeration, root penetration, microbial activity, seedling emergence, water holding capacity and permeability (33-35). Higher sodium concentration contributes to sodium-induced dispersion, leading to reduced hydraulic infiltration and surface crusting. In contrast, the smaller size of calcium and magnesium ions promotes clustering of clay particles and maintains soil flocculation. They compete with sodium ions for binding sites on clay particles, thereby reducing sodium-induced dispersion (36). Secondary sodification is mainly caused by the increased use of sodic water for irrigation, which hinders the hydraulic conductivity of the soil by forming thick clay sodic layers under the surface (37). Globally, production of solanaceous vegetable crops has been significantly limited by salt stress produced by sodic soil (38). For example, in sodic soil, the growth of vegetable crops such as tomatoes, asparagus and beans has been found to be more vulnerable to sodicity than salinity (39). Furthermore, increased sodicity levels lead to a decrease in chlorophyll and non-reducing sugar content, while proline, reducing sugars and total sugar content increase. These changes in physiological and biochemical compounds substance affect the growth and yield of rice varieties, including White Ponni (WP), TRY 1, CO 43, TRY 2, CSR 27 and TRY 3 (40). The availability of micronutrients like iron, copper, manganese, molybdenum and zinc is reduced in sodic soil due to poor solubility, leading to deficiency symptoms in crops (41).

Mechanisms and role of calcite solubilizing and sulfur-oxidizing bacteria in alleviating calcium stress in crops

Calcareous soils are rich in calcium carbonate, which results in high alkalinity and restricts nutrient availability to plants (42). Soil microbes play a vital role in mobilizing plant nutrients, thereby influencing plant growth and stress responses (43). Solubilization of calcite carbonate increases bicarbonate concentrations, which enhances the soil buffering capacity and improves nutrient availability (13). Calcite solubilizing bacteria possess the potential to solubilize calcium carbonate, thereby enhancing crop growth (44). Calcite solubilizing bacteria are a group of plant growth promoting rhizobacteria (PGPRs) that help in converting the insoluble form of calcite into a soluble form of calcium (45-47). The presence of these bacteria in the microbial community varies with calcium level in the soil, indicating their essential role in maintaining calcium availability (43). The primary mechanism involved in calcite solubilization includes the release of organic acids such as citric, gluconic and acetic acids, along with the secretion of sanazine pigment (47, 48). The calcite solubilizing potential of *Azotobacter salinestris* YRNF3 has been demonstrated via the production of organic acids such as formic, lactic and acetic acids and was identified as a survival mechanism that enables the bacterium to obtain calcium in low-nutrient soil environments (44). The types of organic acids produced by microbes are influenced by factors such as pH, temperature, organism and nutrient availability. Formic acid was produced by diazotrophic *Azotobacter salinestris* YRNF3 under low nutrient conditions, whereas lactic acid was produced at higher temperatures (49, 50). *Bacillus subtilis* SSRCI02 synthesizes a wider range of organic acids, such as gluconic, propionic, acetic, lactic, phytic and fumaric acids in the presence of calcium carbonate (47). *Brevibacterium* species. SOTI06 has been found to release 18.6 % of inherent calcium carbonate as calcium (Ca^{2+}) (47).

Apart from calcite solubilizers, sulfur-oxidizing bacteria also play a crucial role in acidifying the calcareous soil, thereby increasing nutrient availability. Sulfates and phosphates are made available during sulfur oxidation, primarily due to acidification caused by the release of sulphuric acid (51). Among sulfur oxidizers, *Thiobacillus* species are important in agriculture and have been reported as common inhabitants of soil (52).

Mechanisms and role of sodium salt tolerant/ accumulating bacteria in alleviating stress in crops

To overcome the salt stress, crops naturally adapt through a wide range of physiological and biochemical mechanisms (53-55). Plants employ several mechanisms to deal with excess Na^+ and Cl^-; however, all of these are energy intensive, which has a detrimental effect on crop growth (56). The most used strategy to control salt uptake is achieved by enzymes present in root cell membranes, which actively pump Na^+ and Cl^- back into the soil (57). Additionally, numerous vital functions have been carried out by microbial communities, including improving plant growth by reducing salt stress through antioxidant and Osmoprotective activity. Salt-tolerant PGPR regulates the uptake of Na^+, K^+ and Ca^{2+}, along with enhancing auxin production (58). The application of PGPB (plant growth-promoting bacteria) has emerged as a promising strategy to improve crop development by mitigating the adverse effect of sodicity. These bacteria secrete organic acids and indole-3-acetic acid (IAA), facilitate osmolyte accumulation, produce siderophores and exopolysaccharides (EPS) and contribute to biofilm formation. This mechanism contributes to enhance plant tolerance to sodicity (59). For instance, *Staphylococcus cohnii* NBRI YB1.6 and *Bacillus aryabhattai* NBRI YN4.4 have been observed to produce elevated levels of alginate and exopolysaccharide (EPS) under sodic conditions. This increased secretion forms a protective layer, thereby improving microbial persistence and resilience (60). Similarly, galacturonic acid is one of the extracellular polymeric substances (EPSs) found in *Rhodopseudomonas palustris*. Under aqueous conditions, these ESPs interact with sodium cations, contributing to microbial salt tolerance (61). Likewise, species such as *Enterobacter*, *Paenibacillus*, *Bacillus*, *Microbacterium* and *Burkholderia cepacian*, have been observed to produce a biofilm near the root zone, thereby reducing the Na^+ intake in wheat plants under sodic condition (62). Utilization of PGPR-C3, a halotolerant rhizobacterial consortium, increased K^+ absorption by limiting the accumulation of Na^+ ions in the root zone (38). Similarly, exopolysaccharide-producing sodium-tolerant bacteria (EPS-STB) reduces sodic stress by restricting the uptake of sodium salt (63). For instance, the salt-tolerant ability of gladiolus has been enhanced by the application of *Bacillus pumilus,* a bacterial consortium that increased K^+ ions uptake when compared to Na^+ ions, resulting in a low Na^+/K^+ ratio (64). Additionally, biochemicals like total soluble solids (TSS) and proline contribute salt stress tolerance in gladiolus (64). Likewise, the combined application of PGPR consortia significantly increased the K^+ and Ca^{2+} concentrations, fresh weight and shoot length in wheat, exhibiting a synergistic effect that enhanced plant growth and yield, thereby reducing salt stress (65).

Reclamation of salt affected soils

Calcareous Soil

To transform the infertile soils into fertile ones, it is essential to apply microbial species that are native to calcareous soils that can break down bound micronutrients into forms readily available to plants (27). In soil, beneficial bacterial microflora plays a significant role as a salt-solubilizing, salt-mobilizing and salt de-mineralizing agent (27). Kidney-bean plants cultivated in calcareous soil treated with *Bacillus* bioinoculants exhibited increased uptake of micronutrients such as Fe and Zn (27). The physical, chemical and biological characteristics of calcareous soil can be significantly enhanced by the application of 5 t ha^{-1} of sulfated press mud cake along with *Trichoderma viride* and phosphorus-solubilizing bacteria (66). Similarly, the application of arbuscular mycorrhizal fungi (AMF) and phosphate solubilizing bacteria (PSB) in calcareous soil can effectively enhance the availability of immobile P in a sustainable manner (67). AMF has been reported to significantly improve potato farming under organic cultivation, along with decreasing environmental pollution by reducing the use of external fertilizers (68). Furthermore, the diazotrophic bacterium *Azotobacter salinestris* YRNF3 can be used as a bio-agent to improve the properties of calcareous soils, including enhancing soil pH and nutrient availability (44). The role of microbes in the reclamation of calcareous soil is explained in Table 1 and Fig. 2 demonstrates how these microbial population can benefit plants.

Sodic Soil

Microbial applications to sodic soil have shown significant potential in establishing a rhizosphere conducive to crop growth (78). Various bacterial genera, including *Agromyces, Pseudomonas, Bacillus, Paenibacillus, Enterobacter* and *Burkholderia*, exhibit plant growth-promoting traits that aid their host plants (63). For example, the application of *F. helveticus* L2C1L2, a sodicity-tolerant, EPS-producing plant growth-promoting bacterium, has been reported to enhance rice growth by forming a biofilm around the root surface, thereby reducing sodium ion uptake. Additionally, in sodic soils, the production of EPS contributes to the formation of stable soil aggregates (63).

Integrating organic matter and microbial inoculants has emerged as an effective and eco-friendly strategy for managing sodic soils. For instance, *Trichoderma* is a multifunctional microbe widely utilized in crop production as a biological control agent (79). Similarly, the combined application of salt-tolerant bacteria and organic amendments has been shown to enhance the growth and oil yield of *Ocimum basilicum* (80).

Likewise, halotolerant plant growth-promoting rhizobacteria (H-PGPR) offer a promising strategy for sustainable crop production in sodic soils (81). Under such conditions, inoculating wheat seeds with halophilic bacteria has been found to enhance crop growth, increasing grain and straw yields by 18.1 % and 24.2 % respectively, while reducing soil pH from 9.4 to 8.6 (82). Moreover, EPS-producing bacteria contribute significantly to mitigating sodic stress by limiting sodium ion uptake in plants. To enhance this effect, it is essential to increase the colonization of EPS-producing, sodic-tolerant plant growth-promoting bacteria, as they play a vital role in improving plant resilience under saline conditions (63). The role of microbes in sodic soil reclamation is summarized in Table 2, while their benefits for plant growth are illustrated in Fig. 2.

Conclusion and prospects

Calcareous and sodic soils are categorized as salt-affected soils, both posing significant challenges to crop production. Sodic soils, characterized by their high sodium concentration, are widespread globally. Similarly, calcareous soils are prevalent across many Indian states and play a crucial role in the world's food supply. To address the growing demands of the world's population, it has become essential to enhance the fertility of calcareous soils. Numerous techniques have been developed to tackle these problems, among which microbial reclamation has emerged as an approach to improve plant growth and yield in salt affected soils. Application of beneficial microorganisms enhances nutrient availability, improves fertility, reduces the use of chemical fertilizers, suppress pathogen attacks and decrease salt accumulation in these soils. The application of organic acid-producing microbes can create favorable conditions, such as an optimal pH environment, that enhances nutrient availability and facilitate mobilization of P, Zn and Fe levels in the salt affected soils. Sulphur plays an important role in altering the pH of calcareous soil (70). The application of sulfur-oxidizing bacteria in agricultural soil can enhance the

Table 1. Role of microbes in the reclamation of calcareous soil

S.No	Crops	Treatmental combination	Treatmental effect on crops	References
1.	Sugarcane	SPMC (Sulphitated press mud cake) @ 12.5 t/ha + T. *viride* + PSB.	Macronutrient and micronutrient uptake was higher.	(69)
2.	Maize	Phosphate solubilizing bacteria + cyanobacteria	Increase in yield parameters, including grain weight, grain yield and straw yield. Grain showed an increased uptake of NPK. Carbohydrate content was higher under the PSB treatment, while protein content was higher in the cyanobacteria treatment.	(70)
3.	Wheat	MSC (elemental sulfur & farmyard manure enriched with sulfur-oxidizing bacteria) + NPK and ½ P.	Improved nutrient availability, particularly phosphorus and micronutrients.	(71)
4.	Maize	LAB strain (*Limosilactobacillus* species LF-17)	It aids the seed germination, growth and chlorophyll biosynthesis of maize seeding.	(72)
5.	Sunflower	A mixture of rhizobacteria strains, namely *Azotobacter chroococcum* ZCR, *Azospirillum brasilense* SBR and *Klebsiella pneumoniae* KPR (HALEXbio-*formulation*)	Reducing the severity rating of sunflower root-rot disease. Additionally, treating with rhizobacteria significantly enhances the plant growth, yield and oil content.	(73)
6.	Maize and Wheat	Arbuscular Mycorrhizal Fungi + *Bacillus* species PIS7 in combination with RP (Rock	Enhanced Plant grain yield and phosphorous uptake. Increased the PSB population density, Maize and wheat root colonization post-harvest soil properties.	(67)
7.	Common bean	Combined application of PSB (*Pseudomonas mallei* + *Pseudomonas cepaceae*) and nano -phosphorus	Highest level of plant growth , yield, P contents, PSII efficiency and total chlorophylls .	(74)
8.	Wheat	PSB strains (ENPSB 1, 2 and 3)	Increase in the dry weight and P content.	(75)
9.	Common bean	Application of two *Pseudomonas* species; *P. mallei* and *P. cepaceae* in 1:1 ratio)	Increased enzymatic activities of phosphatases and phytases. Also enhanced the solubility of nutrients such as N, K, Fe and Mn.	(76)
10.	Sorghum	Fe-EDTA + PGPR strains (*Pseudomonas putida* P159, *Pseudomonas fluorescens* T17-24, *Bacillus subtilis* P96)	It facilitates plant growth and provides essential nutrients to the plants.	(77)
11.	Kidney-bean	*Bacillus* bioinoculants	Increased uptake of micronutrients such as Fe and Zn.	(27)

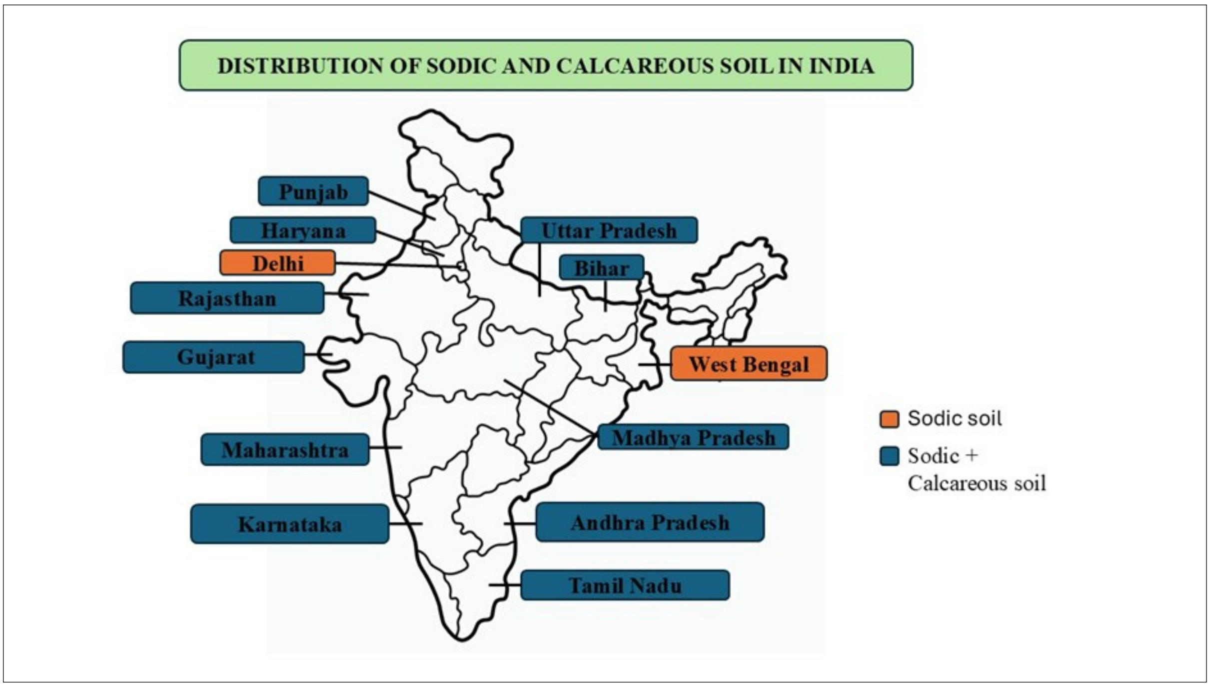

Fig. 1. Distribution of sodic and calcareous soil in India.

Table 2. Role of microbes in the reclamation of sodic soil

S.NO	Crops	Treatmental Combinations	Treatmental effect on crops	References
1.	Rice-Wheat	Application of 10t ha^{-1} of microbial enriched MSW compost + 25 % GR gypsum.	Highest grain yield of rice-wheat.	(83)
2.	Rice	*Franconibacter helveticus* L2C1L2 (a sodic tolerant bacteria)	Enhanced dry matter yield.	(63)
3.	Wheat	*Lysinibacillus* species	Enhanced seed germination percent, shoot length and seedlings vigor index.	(84)
		Lysinibacillus fusiformis	Higher root growth is observed in terms of root length and fresh and dry weight of wheat.	
4.	Tomato hybrid NS585	PGPR-C3, a Halotolerant rhizobacterial consortium (*Bacillus* and *Lysinibacillus* species)	Increased lycopene content and tomato yield.	(38)

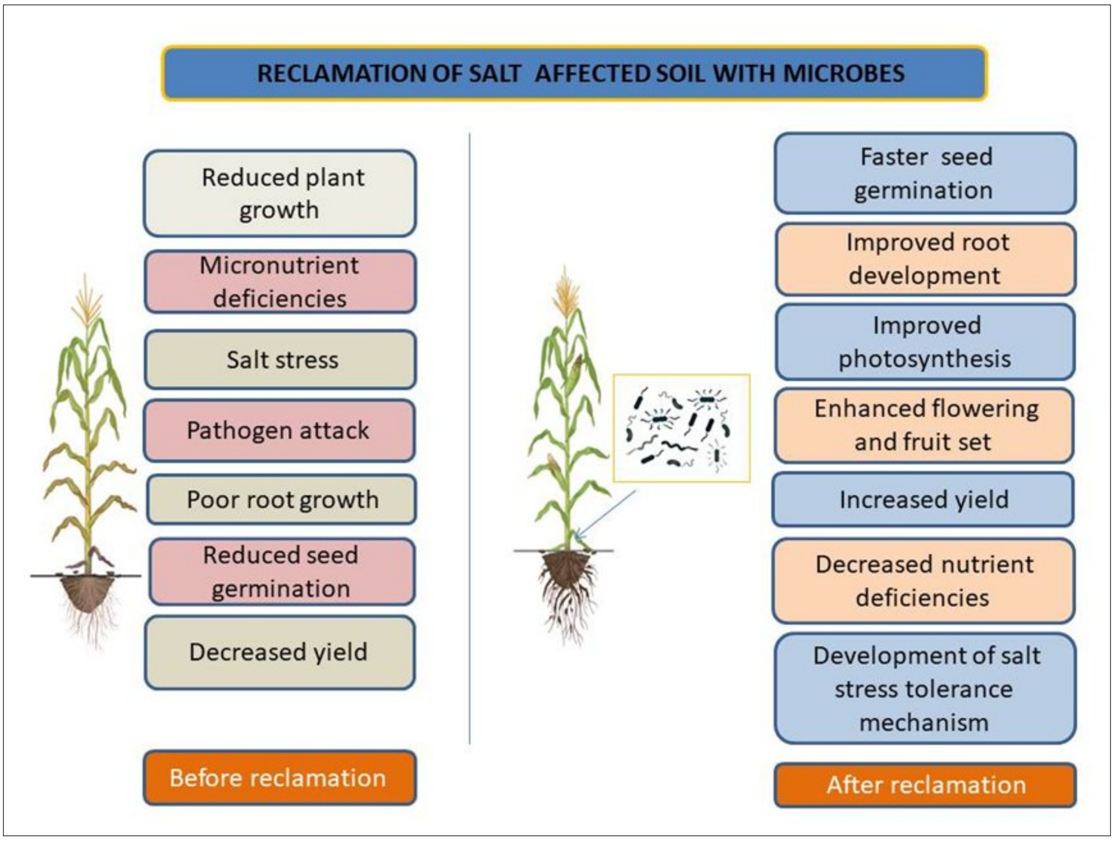

Fig. 2. Reclamation of salt affected soil with microbes.

productivity of calcareous soils (85). Further investigation is imperative to examine the use of biofertilizer combined with elemental sulphur as an additive to improve the physiochemical properties of the soil (70). Traditional methods such as application of gypsum and lime have also found to be more effective. However, combining these traditional methods with microbial strains can further accelerate the soil reclamation process and aid in developing cost-effective bioformulations for large-scale application. Future research should focus on field level validation of microbial techniques, development of site-specific microbial consortia along with integration of these practices into agricultural management systems. By implementing these strategies, the harmful effects of salt affected soils can be reduced, thereby ensuring food security for an expanding global population.

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Authors' contributions

TM and JPB conceived the concept and wrote the manuscript. TM designed the diagrams and tables. MK and HSM reviewed and revised the manuscript. JPB, RPT, MK, RN, TM, HSM, BK and AR finalized the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest : Authors do not have any conflict of interests to declare.

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