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Review Paper

Bioamelioration of Salt-Affected Soils: Restoring Soil Health to Safeguard Community Well-being

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Abstract

Soil salinity is a global challenge that threatens agricultural productivity, food security, and human health. Salt-affected soils (SASs) currently cover millions of hectares worldwide, with the affected area expected to increase due to primary and secondary salinization, climate change, unsustainable irrigation, and industrial activities. Salinity not only reduces crop yields but also enhances the mobility of heavy metals, increasing their uptake by plants and subsequent entry into the food chain and drinking water, ultimately affecting human beings. Elevated soil and water salinity have been directly associated with hypertension, cardiovascular diseases, pregnancy complications, gastrointestinal issues, and increased vulnerability to infectious diseases. Bioamelioration involves the use of halophytes, plant growth–promoting microbes, organic amendments, biochar, mycorrhizal fungi, and vermiremediation, and appears as an eco-friendly and sustainable alternative to physical and chemical methods of soil reclamation. These biological approaches improve soil structure, nutrient cycling, and stress tolerance in plants, while reducing toxic metal mobility and safeguarding ecosystem health. Integrating bioamelioration with nanotechnology, precision agriculture, and one health approaches presents a promising pathway toward sustainable soil management. This review highlights the interconnectedness between soil quality of salt-affected soils and human well-being and underscores the urgent need for scalable, nature-based reclamation strategies to restore degraded soils and secure food and human health security for an ever-increasing population.

Keywords: Bioamelioration, Phytoremediation, Food security, Bio-inoculant, Nano-remediation

Introduction

Good human health indirectly depends on soil health and it is essential to grow crops, provide food, and support populations. It sustains vital ecological functions as well as a variety of environments (Munzel *et al.,* 2023). The existence of about 6.73 million hectares of unreclaimed salt-affected soils (SASs) causes India to suffer economic losses of \$US ~ 3.0 billion every year. Future estimates suggest that the area of SASs would expand to around 16 million hectares by 2050 as a result of poor irrigation techniques and climate change, which might result in a considerable increase in losses. One of the main obstacles to attaining land degradation neutrality, raising agricultural production, and maintaining food security in India is managing the SASs (Kumar *et al.,* 2022). Over 4.24 million km² of topsoil globally is currently affected by salinity, significantly impacting crop production and food security (FAO, 2024). Twenty percent of cultivated land and 33% of irrigated agricultural lands are already affected by salinity (Mohanavelu *et al.,* 2021).Global estimates show that 4.24 million km² of topsoil and 8.33 million km² of subsoil are affected by salt (Shokri *et al.,* 2024). The annual rate of increase in salt-affected lands is approximately 10%, with 2 million hectares of land lost each year to salinization (Basak *et al.,* 2022). FAO's global map of salt-affected soils reveals that over 1,381 million hectares, 10.7 percent of global land, are affected, with Australia, Argentina and Kazakhstan among the most impacted countries (FAO, 2024). India has 6.74 million hectares of soil that is affected by salts comprising both salinity and alkalinity (Kumar and Sharma, 2020). It includes saline soils -2.956 m ha and alkaline soils -3.771 m ha (Arora and Sharma, 2017; Arora *et al.,* 2016). Gujarat (2.23 million ha), Uttar Pradesh (1.37 million ha), Maharashtra (0.61 million ha), West Bengal (0.44 million ha), and Rajasthan (0.38 million ha) are the major states that cover approximately 75% of the salt-affected soils area (Mandal *et al.,* 2018).

Soil degradation resulting from salinity is a major environmental constraint with severe negative impacts on agricultural productivity and sustainability, particularly in arid and semi-arid regions of the world (Hasanuzzaman *et al.,* 2014). High salinization and heavy metals contamination may have the capability to deteriorate the quality of the soil (Gao *et al*., 2011; Jadia and Fulekar, 2008; Singh, 2015). The salinity can enhance to some extent the mobility of heavy metals in soil, which may lead to increase the salinity stress for plant growth (Ali *et al*., 2013; Qu *et al*., 2011). Similarly, this may also promote the translocation of heavy metals from roots to shoots (Acosta *et al*., 2018; Hasan *et al*., 2017). Various abiotic factors can produce soil salinity including the application of contaminated salty irrigation water (containing high concentration of salts), seawater in the coastal region through tidal estuaries or mixing of sea spray with rainwater in coastal regions, intrusion saltwater into freshwater aquifers and saline industrial water (Arora *et al*., 2017). Approximately 95% of the food that humans eat comes from soil (FAO, 2015). Global food production must rise by 35–56% by 2050 as the population continues to expand and living standards rise (van Dijk *et al.,* 2021).

Bio-amelioration consists of use of biological agents, such as plant growth-promoting bacteria, halophytes, and organic amendments for improving soil health, enhance plant growth, and mitigate the adverse effects of salinity stress (Sahab *et al.,* 2021; Samantary *et al.,* 2024). As a sustainable and environment friendly means of restoring damaged agroecosystems, bio-amelioration of salt-affected soils is gaining popularity as a potential substitute for conventional techniques that could have negative environmental effects (Hoque *et al.,* 2022). Biological interventions, including halophilic microbial inoculants, AMF, algae, seaweed extract (biostimulant), phytoremediation, biochar, organic amendments, and nanotechnology-enhanced bioformulations, (Fig. 4) have demonstrated significant potential in mitigating salt-induced stress by modulating soil microbiota, enhancing nutrient dynamics, improving rhizospheric stability, and promoting ionic equilibrium (Chadha *et al.,* 2025). Bioremediation is a natural process that is widely accepted by the public and ensures the complete destruction of hazardous contaminants without transferring pollutants between soil, air, and water (Fig. 2). It allows for on-site treatment, which minimizes disruption, and is generally more cost-effective than conventional methods. However, there are also some limitations: bioremediation is restricted to biodegradable compounds, and sometimes the by-products produced may be toxic. It also requires site-specific conditions to be effective, and in the case of complex sites, more research is needed. The soil becomes saline due to excess salts, which is a serious hazard to both the environment and ecosystem health and agricultural productivity. One billion hectares across 100 nations are affected by the widespread issue of soil salinity (Singh, 2022). Dryland and waterlogged salinity has been linked to three major possible effects on human health (Fig. 1): changes in the ecology of the mosquito-borne Ross River virus; wind-borne dust and respiratory health; and the effects of salt-induced environmental degradation (Jardine *et al.,* 2007).

In the past decade, studies on the impact of saline drinking water on health in Bangladesh were bolstered (Khan *et al.,* 2008, 2011, 2014; Vineis *et al.,* 2011; Rasheed *et al.,* 2014 ; Talukder *et al.,* 2017). Excessive salt intake is known to be associated with high blood pressure (Aburto *et al.,* 2013), and hypertension is a major risk factor for stroke and cardiovascular diseases (WHO, 2002). Rahman *et al.* (2017) drawing conclusion on peoples' perception from southern coastal zones of Bangladesh, reported that due to the increasing salinity, local population most often suffer from skin diseases, diarrhea, indigestion, gestational hypertension, and blood pressure. The mean values of systolic and diastolic blood pressure were higher in those children who were born and living in the high sodium areas (Hofman *et al.,* 1980). Shohel *et al.* (2011) reported that rural people in South-Western coastal areas of Bangladesh suffer from waterborne diseases

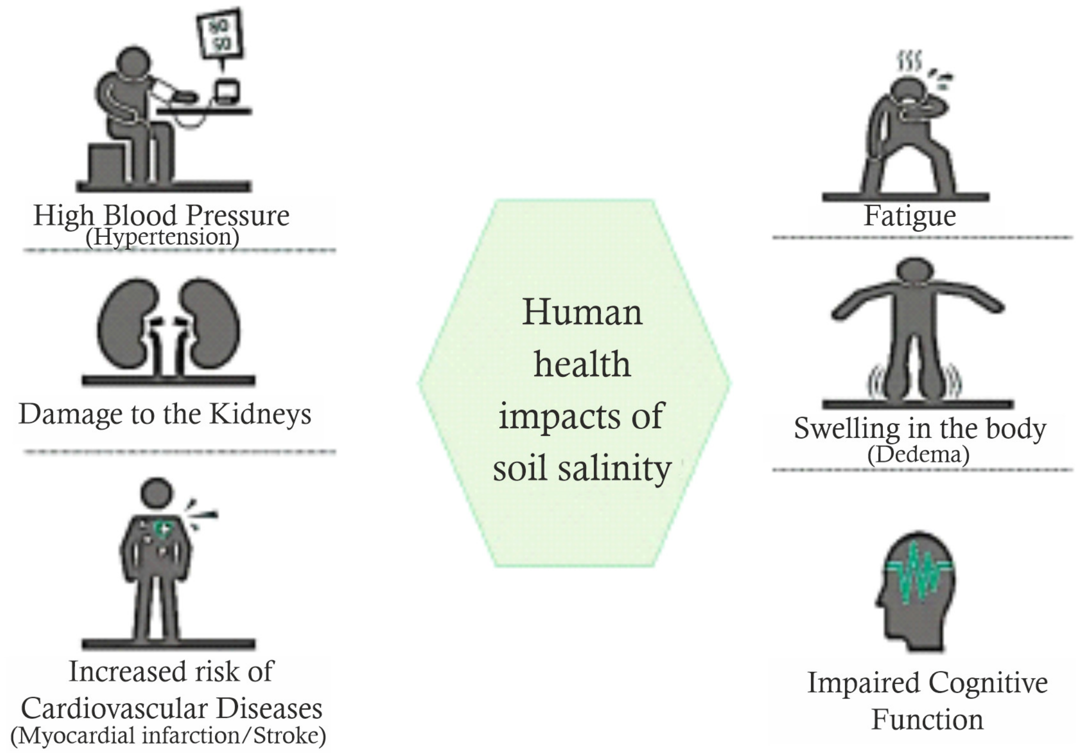

Fig. 1 Impact of soil salinity on human health

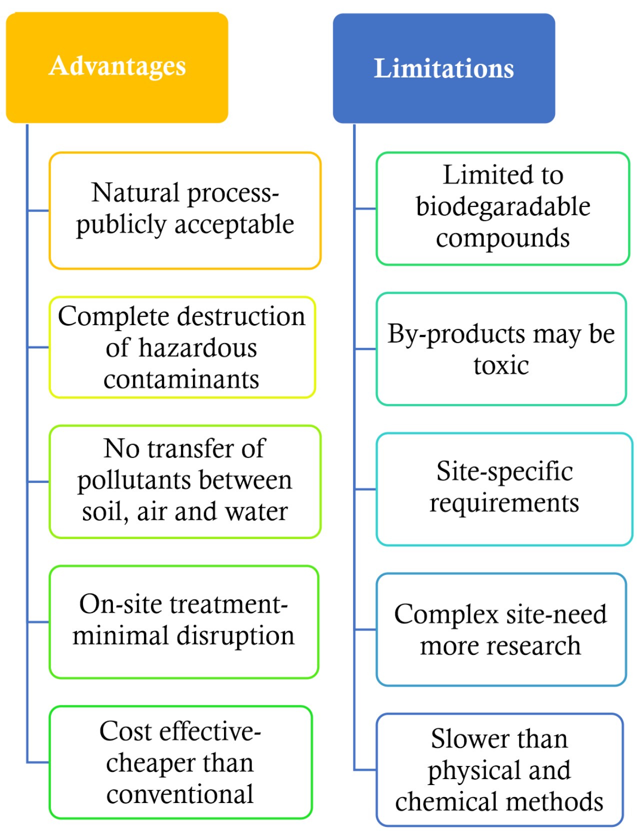

Fig. 2 Advantages and limitations of Bioamelioration (adapted from Ajona and Vasanthi, 2021)

including dysentery, diarrhea, and skin diseases very frequently due to use of saline water. The total hazard index (THI) values of nitrate and fluoride exceeded limits in Southern India, posing health risks to adults and children due to saline water intrusion into groundwater (Agarwal and Dhakate, 2024). An elevated salinity in drinking water is associated with higher risk of hypertension, particularly in young coastal populations of Bangladesh (Talukder *et al.,* 2016).

Drinking Water Contamination

Soil salinization, the buildup of soluble salts in the soil, is a major source of saline groundwater and surface water. This makes water unsuitable for drinking without expensive and energy-intensive treatment.

- **Hypertension and cardiovascular disease**: A high intake of sodium chloride (common table salt) is strongly linked to high blood pressure (hypertension), which is a leading risk factor for premature death worldwide (Han *et al.,* 2025). Populations living in areas with high soil salinity often rely on saline groundwater sources for drinking, leading to a much higher daily salt intake than is safe.

- **Pregnancy complications**: Studies in coastal regions affected by salinity have shown a clear link between the consumption of saline drinking water and a higher risk of preeclampsia and gestational hypertension in pregnant women. These conditions are characterized by dangerously high blood pressure during pregnancy (Rahman *et al.,* 2023).
- **Laxative effect**: High levels of magnesium and sodium sulfates in drinking water can have a laxative effect, causing dehydration and other gastrointestinal issues (Bellini *et al.,* 2021).

Food and Nutrition

Soil salinity directly impacts food production, which in turn affects human health through nutrition and livelihood.

- **Reduced crop yields and food scarcity**: Salt accumulation in soil inhibits a plant's ability to absorb water and nutrients, leading to decreased crop yields or even the complete failure of crops. This poses a serious threat to **food security**, particularly in arid and semi-arid regions that rely on irrigation, and can lead to malnutrition and hunger (Khondoker *et al.,* 2023).
- **Livelihood and mental health**: For rural and urban communities that depend on agriculture affected by soil salinization can lead to economic losses, unemployment, and forced migration. This can cause significant social and psychological stress, leading to a rise in mental health problems and a decline in overall community well-being (Sanga *et al.,* 2024; Dasgupta and Basu, 2023).
- **Heavy metal contamination**: Saline conditions can mobilize heavy metals like arsenic, lead, and cadmium that are naturally present or have been introduced into the soil. These metals can then be absorbed by crops and accumulate in the food chain, or leach into water sources, creating a toxic cocktail that poses a serious risk of poisoning (Table 1) (Angon *et al.,* 2024, Acosta *et al.,* 2011, Zhang *et al.,* 2016).

Different Ways for Sustainable Biological Remediation Practices for Sustaining Soil Health

A sustainable method for remediating contaminated soils is bioremediation, which involves using microorganisms (mostly bacteria and fungi) to clean up contaminated places (Fingerman and Nagabhushanam, 2016). Numerous techniques have been put forth for soil remediation since the 1970s, because of their efficacy and affordability, bioremediation techniques have become more well-known among these techniques.

Bio-inoculants

Bio-inoculants can be used to increase the crop yield and enhance the soil structure and nutritional capacity of stressed soil (Table 2). Microbial consortia in aquatic ecosystems break down oil spills, avoiding long-term environmental degradation and promoting marine biodiversity (Andrey *et al.,* 2021). Bioremediation methods are increasingly being incorporated into industrial waste management programs because of their considerable reduction in pollutant levels and cleaning expenses compared to older methods (Gupta *et al.,* 2025). Microbial solutions can revolutionize a variety of industries, spanning agricultural production, environmental cleansing, economic benefits, and sustainability over the long term, as per quantitative estimations (Verstraete *et al.,* 2022). Many plant growth promoting-bacteria (PGPB) produce compounds such as osmoprotectants, which help in the regulation of osmotic stress in plants or trigger the defense

Table 1. Heavy Metal Behavior in Salinized Soils

Soil Condition	Heavy Metal Effect	Human Risk Pathway
High salinity (NaCl)	Increases solubility and uptake	Crop consumption, water
High heavy metals with salinity	Combined toxicity, lower soil health	Direct soil, food crops
Low pH (common in saline soils)	Further increases metal mobility	Enhanced food chain risk

Table 2. Microbial species used for bioamelioration

Name of microbial species	Mechanism used	Reference
Glutamicibacter sp. and *Pseudomonas* sp.	Antioxidant defense	Hidri *et al.,* (2022)
Pseudomonas aeruginosa	Biosurfactant production	Ebadi *et al.,* (2017)
Desulfovibrio halophilus	Bioreactor	Eskandari *et al.,* (2019)
Bacillus, Trichome and *Candidatus methanopenens*	Antioxidant defense	Wen *et al.,* (2024)
Bacillus flexus	Phytoremediation	Xiong *et al.,* (2020)
Exiguobacterium sp. JBHLT-3	Biodegradation	Bai *et al.,* (2021)
Halobacillus spp.	Biodegradation	Ibrahim *et al.,* (2020)
Enterobacter sp. P23	Enzymatic secretion	Sarkar *et al.,* (2018)
Arbuscular mycorrhizal fungus (AMF), *Glomus mosseae, Mortierella* sp.	Enzymatic secretion	Zhang *et al.,* (2014)

mechanisms of a plant itself (Ha-Tran *et al.,* 2021). PGPB inoculation can enhance drought tolerance among crops, enabling them to survive prolonged water scarcity conditions (Gowtham *et al.,* 2022). Microbial inoculants have been shown to enhance the yield and water-use efficiency in salt-stressed crops through the mitigation of salinity effects on growth. Various halophilic microorganisms, including plant growth-promoting rhizobacteria (PGPR), contribute to soil remediation by facilitating ion homeostasis and producing organic acids. Additionally, these microbes support nutrient cycling through biological nitrogen fixation and phosphate solubilization, thereby improving soil fertility and plant growth under saline and sodic conditions (Giri *et al.,* 2007; Gaikwad *et al.,* 2024).

Phytoremediation

Phytoremediation consists of the use of plants and associated microbes to reduce the concentration and/or toxic effects of contaminants in the environment (Greipsson *et al.,* 2011). Halophytes are plants that exhibit high salt tolerance, allowing them to survive and thrive under extremely saline conditions (Table 3) (Meng *et al.,* 2018).

i. ***Phytodesalinization:*** Phytodesalinization is a specific type of phytoextraction that uses the capacity of some plants to take up and translocate salts from soil to above ground plant tissues. The mechanism that makes halophytes important tools for desalinisation include salt exclusion, salt excretion, salt compartmentation (Sarath *et al.,* 2021). *Hyperaccumulators* are extremely specialized plants that can accumulate salts from soil in their aboveground tissues at remarkably high concentrations (1-10%) (Yensen and Biel, 2006). Examples of plants with potential for phytoextraction strategies are: *Avicennia* spp., *Aegialitis* spp., *Aegiceras* spp., and *Acanthus* spp (Hasanuzzaman *et al.,* 2014). The primary determinants of phytoextraction efficiency are the short lifecycle, resistance to oxygen deficient conditions, translocation factor (TF), which are employed in the screening of hyperaccumulating plants (Devi *et al.,* 2016; Mazumdar and Das, 2015).

Table 3. Halophytes used for phytoremediation of salt affected soils

Name of plant species	Soil properties influenced	Reference
Alhagi maurorum, *Tamarix aphyll and Salvadora persica*	Cd and Pb	Waris *et al.,* (2022)
Salicornia europaeae, Halocnemum strobilaceous	Na, Ca and K	Ahmadi *et al.,* (2022)
Salvadora persica L.	Zn, Cr, and Cu	Mujeeb *et al.,* (2023)
Atriplex cinerea, Frankenia thymifolia	Desalinisation of water	Dezvareh *et al.,* (2023)
Sedum aizoon	Ca and Mg	Mu *et al.,* (2021)
Medicago sativa L. , *Zea Mays*	Bulk density, Total salinity, Total porosity	Li *et al.,* (2022)
Scirpus littoralis, *Typha orientalis*, *Setaria sphacelata*	Na^+	Trang *et al.,* (2023)
Zygophyllum eurypterum and *Aerva javanica*	Cu, Pb and Zn	Mousavi and Moudi, (2020)
Sesuvium portulacastrum	Na, K and Ca	Ramasamy *et al.* (2017)

ii. ***Phytostabilization:*** Phytostabilization—which focuses on metal immobilization in the rhizosphere - has a lot of promise for soils with moderate to high levels of metal contamination (Cundy *et al.,* 2016; Hrynkiewicz *et al.,* 2018). *Tamarix africana* is well adapted to the contaminated saline soils, stored the contaminants in the roots, and had small concentrations of hazardous elements in the shoots (Santos *et al.,* 2017).

iii. ***Phytomanagement:*** Phytomanagement makes site remediation an attractive option for stakeholders due to the environmental, economic and social benefits that can be obtained, while mitigating the risk resulting from the presence of the contaminants (Phang *et al.,* 2024, Moreira *et al.,* 2021). This technique is usually carried out by growing deep-rooted legume plants such as alfalfa and sesbania and then incorporating their residues into the topsoil layer (Razaq *et al.,* 2016), and many works proved the effectiveness of this method. *Atriplex halimus* has been recommended as phytomanagement crop to reclaim highly calcareous sodic soils (Gharaibeh *et al.,* 2011).

Vesicular arbuscular mycorrhizae

Enhanced growth of mycorrhizal plants grown in saline environment has been related partly to mycorrhiza mediated enhancement of host plant phosphorus nutrition (AlKaraki, 2001). Growth increases may be attributed directly to enhanced photosynthesis associated with the increased P uptake by plants (Diets and Foyer, 1986). The presence of *G. etunicatum* inside the roots of *C. tinctorius* increased plant salt tolerance. Mycorrhizal plants were more effective in increasing P, Zn, K, and Fe acquisition under saline conditions. The higher nutrient acquisition by mycorrhizal plants was the most likely mechanism of salt stress reduction (Tawfic *et al.,* 2002). Mycorrhizal symbiosis (*Diversispora tortuosa*) had marginal (even significantly negative) effects on the mitigation of the ionic ratios (e.g., K^+/Na^+ and P/Na^+), which may be attributed to the increase in Na^+ accumulation and translocation from roots to shoots. Mycorrhizal symbiosis significantly increased the rhizosphere soil TEG content and decreased the soil pH (Ma *et al.,* 2021). Apple trees were inoculated with the AM fungi, *Funneliformis mosseae*, improved apple trees salt tolerance by promoting AM symbiosis through increased carbohydrate content. AMF and dopamine worked synergistically to maintain plant cell membrane stability and improve photosynthesis under high salinity, which improved the salt tolerance of the plants (Gao *et al.,* 2020). In saline environments, plant root and soil colonization by AMF can improve the rhizosphere condition of the soil through strengthening the improvement of organic carbon in the soil, increasing N, P and K pools, improving the content of organic matter, adjusting pH of the soil, and preventing soil erosion (Zai *et al.*, 2021).

Vermiremediation

According to Sinha *et al.* (2008), vermiremediation is the process of using earthworms to remove pollutants from soil. Although vermiremediation is more frequently employed for organic contamination, some research has examined the relationship between earthworms and salts (Eijsackers, 2010; Kavehei *et al.,* 2018). Earthworm casts also significantly altered the soil structure, which facilitates the leaching of salt ions, reducing the salt content of the topsoils (Li *et al.,* 2021). The application of earthworms (*Eudrilus eugeniae*) combined with organic material (compost and vermicompost) reduced soil salinity which may be because that the increasing Ca^{2+} and Mg^{2+} concentration in the soil solution permitted greater leaching of exchanged Na^+ in percolating water (Oo *et al.,* 2015). The studies of Zhang *et al.* (2016; 2018) also showed that epigeic earthworms (*Eisenia fetida*) could decrease soil salt concentration through the improvement of soil structure and water movement drainage in saline alkali soil. Earthworms can decrease the soil pH possibly via the production of humic and fulvic acids through their gut microbes (Drake and Horn, 2007). Oo *et al.* (2015) demonstrated that an earthworm cast could reduce soil salinity by decreasing exchangeable Na^+ and improve maize growth by increasing soil microbial activities and supplying essential nutrients (soil saturated EC

4.26 dS m^{-1}). Earthworms could significantly decrease the salt concentration and increase the soil macro-aggregates and mineral uptakes including the K, Ca, and Mg to promote maize growth (Zhang *et al.,* 2018).

Nano-bioremediation

Nanotechnology has emerged as a promising approach to soil reclamation, offering innovative solutions for mitigating soil salinity and sodicity. Various types of nanoparticles (NPs), including metal based, metal oxide, polymer-based, carbon-based, and modified NPs, have been demonstrated to be effective in improving plant growth under saline conditions (Soni *et al.,* 2024). Nano-biochar has emerged as a long term solution for soil remediation, as it not only modifies saline soils but also aids in plant stress resistance (Faizan *et al.,* 2025). By advancing the use of nano-based amendments, such as nano-gypsum, nano-silicon, nano-compost, and nano-chitosan, in conjunction with salt-tolerant crops and halophytes, the agricultural sector can significantly improve soil productivity and sustainability, and ensure food security in saline-affected regions (Sári *et al.,* 2023; Singh *et al.,* 2025). Silicon nanoparticles have been reported to have physiological and morphological effects on the vegetative characteristics of *Ocimum basilicum* L. (basil) under salinity stress. The significant increase in the growth and development of the basil (*O. basilicum*) plant was observed (Das and Das, 2019).

Comparative Evaluation of Physical, Chemical, and Biological Methods for Soil Reclamation

The comparison of three soil remediation methods—bioremediation, physical remediation, and chemical remediation—based on cost, environmental impact, sustainability, effect on soil quality, scalability, and safety is mentioned in Table 4. Bioamelioration is highlighted as a low-to-moderate cost, environmentally friendly, and sustainable method that uses microbes and plants to clean soil, often improving its quality over time (Chhabra, 2021). It supports soil health and is highly scalable and safe, making it a preferred "green" solution (Ghisman *et al.,* 2025). In contrast, chemical remediation involves high costs due to the use of chemical agents and equipment, carries risks of secondary pollution, may disrupt soil biology, and can leave harmful chemical residues (Riser-Roberts, 2020). It is less sustainable and limited by safety and application concerns.

Table 4. Comparison between physical, chemical and biological methods of reclamation

Criteria	Physical Methods (e.g., land levelling, deep ploughing, drainage)	Chemical Methods (e.g., gypsum/lime application, neutralizing agents)	Biological Methods (e.g., phytoremediation, microbial treatment, organic amendments)
Cost	High initial investment (equipment, infrastructure)	Moderate to high (cost of chemicals, transport, repeated application)	Generally low to moderate (plants, microbes, organic matter are relatively inexpensive)
Environmental Impact	Can cause soil disturbance, erosion, loss of soil biodiversity	Risk of secondary pollution, chemical leaching into water, soil acidification/ alkalinity	Eco-friendly, improves soil health and fertility, minimal negative impacts
Sustainability	Low to moderate (may not be sustainable long-term)	Low (continuous use needed, risk of chemical buildup)	High (enhances natural processes, builds soil resilience over time)
Long-Term Effectiveness	Short- to medium-term (requires periodic maintenance)	Medium (effectiveness depends on continuous application)	High (restores soil functions, long-lasting improvements)
Suitability for Large Areas	Suitable but expensive and labor-intensive	Practical for large areas but costly and may face supply/logistics challenges	Best suited for moderate areas
Community Acceptance	Moderate (seen as disruptive but effective)	Low to moderate (concerns about chemical residues and safety)	High (perceived as natural, safe, and beneficial for environment and health)

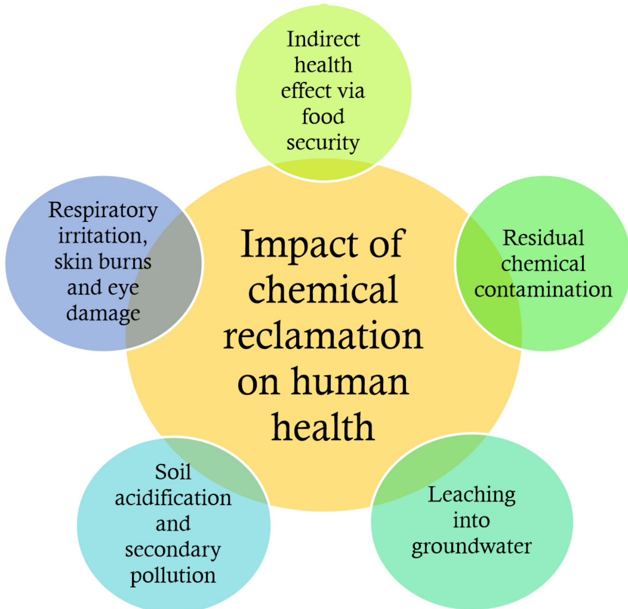

Fig. 3 Impact of chemical reclamation on human health

Physical remediation typically involves techniques like excavation or soil washing, which are effective but often expensive, invasive, and less beneficial for long-term soil health (Tiwari and Tripathy, 2023). Overall, bioremediation stands out as the most eco-friendly and sustainable options for salt stressed soils.

Impact of chemical reclamation on human health

The negative effects of soil chemical reclamation on human health (Fig. 3) mainly come from the fact that it often involves adding or using strong chemical agents to break down, immobilize, or neutralize contaminants and those chemicals (or their byproducts) can themselves be harmful. Excessive or repeated application of gypsum, lime, or industrial byproducts (e.g., phosphogypsum) may introduce impurities such as heavy metals (Cd, Pb, Cr, F) into soils and groundwater (Chernysh *et al.,* 2023). Chemical treatments for pesticide-contaminated soils are quicker when compared to biological treatments. However, a drawback is that the residues generated from the separation techniques used in chemical treatments require extra treatment or disposal, leading to an escalation in project expenses (Shit *et al.,* 2023).

Soil bioremediation with human health

The healthy soil ecosystems contribute to human and environmental well-being by supporting plant growth and enabling soil microorganisms to degrade pollutants. This natural process leads to a cleaner environment, which reduces the presence of harmful substances and pathogens (Sharma *et al.,* 2023). As a result, communities benefit from lower exposure to toxins and a decreased risk of disease. The overall message emphasizes the interconnectedness between soil health, environmental quality, and public health, highlighting that sustaining healthy ecosystems directly supports healthier, safer living conditions for people (Brevik *et al.,* 2020).

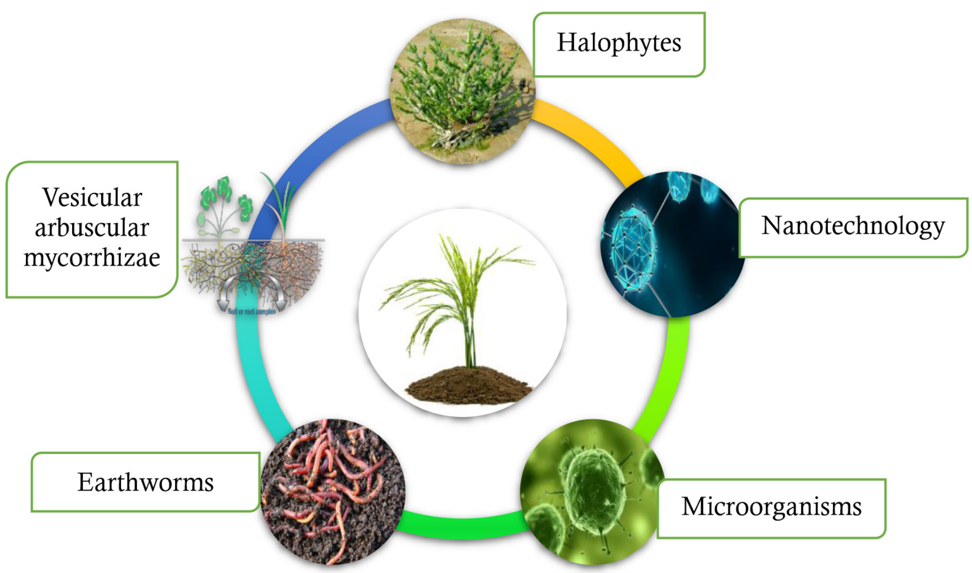

Fig. 4 Different approaches of bioamelioration

One nation, one health

In parallel, the concept of One Health likewise works across the human–animal–environment interface, highly relevant for the goals of Soil Security. The relationship between Soil Security and One Health remains largely unexplored, despite the notable perceived overlap in objectives between these concepts. One example is that soils are home to more than 25% of global biodiversity (Bach *et al.,* 2020) and more than 95% of the world's food comes from soil and soil organisms (Kopittke *et al.,* 2024); thus soils are vital for sustaining the health of humans, animals, ecosystems, and the planet—a key goal of One Health. The soil–human–animal–ecosystem nexus underscores the idea that actions affecting one component can have ripple effects on other components in the system. For example, poor soil management practices in agriculture can result in soil degradation, reduced yields and food insecurity; all of which can directly affect the soil, humans, animals and the ecosystem at large (Pozza and Field, 2020; Kopittke *et al.,* 2019).

Future Perspectives and Research Needs

Microbes promote plant growth and stress tolerance, increasing yields on saline soils. Advances in biotechnology will enable development of customized microbial mixes for specific soil types. Combining microbial treatments with precision agriculture and smart delivery systems will optimize effectiveness. Engineered microbes with improved salt tolerance and growth-promoting traits will enhance bioamelioration. Microbial solutions will help mitigate climate change impacts by restoring soil function and sequestering carbon. Policy support and farmer awareness will drive widespread use of microbial bioamelioration in salt-affected regions. Microbial bioamelioration can help mitigate climate impacts on soil health by improving soil carbon sequestration and reducing greenhouse gas emissions through healthier soil microbiomes. Microbial bioamelioration can be integrated with precision agriculture, remote sensing, and soil health monitoring to optimize application and track soil recovery. Smart delivery systems (e.g., encapsulation, seed coating) will improve the survival and effectiveness of bioameliorative microbes in harsh environments.

Conclusion

Soil salinity and heavy metal contamination present intertwined threats to ecosystem sustainability, agricultural productivity, and human health. Salt stressed soils compromise food production, contaminate water resources, and increase the risk of chronic diseases, particularly in vulnerable coastal and arid regions. Biological reclamation methods, especially microbe- and plant-based strategies, provide an effective, economical, and environmentally friendly alternative to conventional remediation approaches. By preventing leaching and immobilizing contaminants, microbial and plant-based systems restore soil fertility and reduce the transfer of toxic elements into the food chain. Recent advances in engineered microbes, phytomanagement, mycorrhizal associations, and nano-bio amendments demonstrate strong potential for large-scale application. The integration of bioamelioration with modern agricultural technologies and supportive policy frameworks can significantly enhance soil health, mitigate climate impacts, and improve human well-being. Ultimately, securing soil health through sustainable biological interventions is indispensable for ensuring food security, environmental protection, and global public health.

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