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Advances in Environmental and Engineering Research

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Review

Phytoremediation: A Sustainable Approach to Combat Soil Salinity

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Academic Editors: Zhenhua Zhang, Xiaohua Long and Jincheng Xing

Special Issue: Remediation and Utilization of Salt-affected Soils

Adv Environ Eng Res
2024, volume 5, issue 2
doi:10.21926/aeer.2402015

Received: March 14, 2024
Accepted: May 31, 2024
Published: June 12, 2024

Abstract

Soil salinization is a significantconstraint affecting the productivity of agricultural land worldwide. This led to the abandoning of the production of farmcrops on colossalland. Soil salinity inversely affects seed germination and plant growth and influences the plant's biological activities like photosynthesis, respiration, plant metabolism, enzymatic activities, hormone regulation, etc. Therefore, efforts are being made to bring the saline soil under cultivation by improving itthrough a proper drainage system to drain out the salts orapplying chemical amendments. However, these options are costly and energy-intensive for employment in large areas on a vast scale. In this direction, biologically cost-effective approaches are also being practiced to improve these degraded lands. Phytoremediation, a plant-based approach to improving degraded soil, may be an appropriate option. This is done by the plantation of salt-tolerant plant species, which can remove and leach down excess salts like sodium (Na^+) from the soil and enhance calcium (Ca^{2+}) salts through the cation exchange process from the root zone. During this process, remarkable properties like soil-aggregates stability, root proliferation, soil hydraulic properties, and nutrient availability to plants are also improved. Such improvement in soil properties facilitates the cultivation of less tolerant plants and improves the environment in general and the climatic conditions by enhancing carbon sequestration.

Keywords

Cation exchange capacity; phytoremediation; nutrient uptake; saline soil; sustainable management

1. Introduction

Salinization is a more fascinating and vital issue facing world agriculture [1], particularly in semi-arid and arid regions, which significantly threatens agricultural productivity and sustainability. These salt-affected soils are found around the boundaries of more than 70 countries [2]. These problematic soils also occupy around 20% of irrigated land globally [3], and in some countries, more than 50% of irrigated land suffers from soil salinization [4].

In the last couple of decades, soil degradation has increased worldwide. The salinization of soils affects the balance between the demands of societies and the functions (goods and services) provided by natural resources (land and water), which in turn impacts the livelihoods of the local population. Due to intensive farming and crops with high input needs, the amount of salt-contaminated soils is increasing [5]. Changing climate is also crucial as the sea level rises and annual groundwater recharge and its extraction is unbalanced, leading to salt accumulation in groundwater used for irrigation [6]. Also, scanty, uneven, irregular rainfall and drought spells followed by high evaporation from the upper soil layer lead to salt accumulation on the upper surface [7].

Soil salinization creates a threat to crop productivity worldwide. A significantarea of around 1500 MHAis affected by salt globally, which causes severe productivity loss [8]. In India, salt-affected soils occupy around 5% of the net cultivated agricultural land (Table 1). It spread from the north (including Jammu and Kashmir and Ladakh region) to the south (in (Tamilnadu), and in the east (in Andaman & Nicobar Islands) to the west in Kutch of Gujrat [9]. However, these salt-affected soils contain some amounts of soluble salts, some of which may act as a source of essential nutrients for the healthy growth of plants, but exceeding a particular limit of these salts in the soil adversely affects the plant growth and its development for most of the crops.

Table 1 Salt-affected soils in India (state-wise share in %).

S.N.	State	Saline soil (Mha)	Alkaline soil (Mha)	Coastal saline soil (Mha)	Total (Mha)
1	Andhra Pradesh	0.0	5.2	6.2	4.1
2	A & N islands	0.0	0.0	6.2	1.1
3	Bihar	2.8	2.8	0.0	2.3
4	Gujarat	71.2	14.3	37.1	32.9
5	Haryana	2.9	4.8	0.0	3.4

6	J & K	0.0	0.5	0.0	0.3
7	Karnataka	0.1	3.9	0.0	2.2
8	Kerala	0.0	0.0	1.6	1.6
9	Maharashtra	10.4	11.2	0.6	9.0
10	Madhya Pradesh	0.0	3.7	0	2.1
11	Orissa	0.0	0.0	11.8	2.2
12	Punjab	0.0	4.0	0.0	2.2
13	Rajasthan	11.4	4.7	0.0	5.6
14	Tamil Nadu	0.0	9.4	1.1	5.5
15	Uttar Pradesh	1.3	35.6	0.0	20.3
16	West Bengal	0.0	0.0	35.4	6.5
17	Andhra Pradesh	0.0	5.2	6.2	4.1
	Total	100 (3.75)	100 (1.71)	100 (1.25)	100 (6.74)

Source- Mandal et al., 2018 [10].

2. Formation of Salt-Affected Soil

Generally, the formation of saline soil occurs whenever climate, soil, and hydrological conditions favor the accumulation of soluble salts in the root zone. In arid and semi-arid regions, less rainfall and higher temperatures lead to more evaporation, less water leaching, and less soluble salt transport. Soluble salts originate in the soil from decomposing primary minerals [11]. Whenever drainage is restricted, and excess amounts of water evaporate from the land's surface in the arid regions, neutral soluble salts move upward, along with the upward movement of water, and accumulate on the surface as a white crust. In non-saline alkali soils, soluble salts are washed down by the limited rainfall in the arid regions when sodium ions replace calcium and other ions from the clay micelle. The clay micelle is then saturated with sodium ions.

2.1 Salt-Affected Soils are Formed Mainly in Two Phases or Processes

1. Salinization process: Salinization is the process of excess accumulation of soluble salts, including several compounds of sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+),sulfates (SO_4^{2-}), chlorides (Cl^-), carbonates (HCO_3^{2-}), and bicarbonates (HCO_3^-). It occurs either naturally or sometimes through human interference. Some significantcauses of soil salinization are:

- Less rainfall in dry regions could not flush out the excess salts
- Irrigation with saline water also increases salt content in the soil
- Removal of deep-rooted vegetation and a raised water table as a consequence
- salt evaporation from seawater submergence areas
- Excess and imbalance use of fertilizers also leads to excess nitrification, accelerates soil salinization

2. Alkalization process: the process of accumulation of exchangeable sodium (Na^+) in the soil moves downward with the limited amounts of precipitation and replaces the Ca^{2+} and forms sodium carbonate (Na_2CO_3), which is further hydrolyzed and forms sodium hydroxide (NaOH) and carbonic acid (H_2CO_3). This carbonic acid dissociates, increasing the hydroxyl ions (OH^+) concentration and pH in the soil solution. In this way, sodium carbonate is mainly responsible for raising the soil pH by more than 9 [12].

3. Effects of Saline Soil on Crop Growth

1. Water availability to plants decreases: higher salt concentration in the soil increases the electrical conductivity (EC) and osmotic pressure of soil solution, which restricts the plant's water uptake from the soil due to less water availability. Even sometimes, high osmotic pressure due to higher salt concentration in the soil solution causes reverse osmosis or plasmolysis (water movement from the plant to the soil). Plants indicate wilting symptoms like yellowing and browning of the leaves, attributed to drought stress and physiological drought.

2. Toxicity of specific ions: poor physical condition and poor aeration of soil lead to higher concentrations of particularions in the root zone, which may reduce the absorption and metabolism of other plant nutrients. The antagonistic behavior of Cl^- with $H_2PO_4^-$, NO_3^-, SO_4^{2-}, $Na^{+,}$ and K^+ might disturb normal and optimum nutrition in plants.

4. Management of Saline Soil

Salt accumulation in soil directly affects the soil structure and soil properties, which causes plant growth-related problems. Managing these soils is a great challenge and involves various techniques to reduce the salt content and improve soil fertility [13].

i. Soil Testing: Test the soil to determine its salt content and composition. This helps in devising a tailored management plan.
ii. Improving Drainage: Poor drainage exacerbates salinity. Installing drainage systems like tiles, ditches, or subsurface drainage can help remove excess salts from the soil profile.
iii. Leaching involves applying large amounts of water to flush out salts from the soil profile. This water carries the salts downward, away from the root zone. However, this method requires proper water management to prevent water logging.
iv. Application of organic matter:Organic materials like compost, farm yard manure, or green manure improve the soil structure, increasing the water infiltration rate. Organic matter promotes soil microbial activity, which may help reduce salinity by breaking down salts.
v. Selecting Salt-Tolerant Crops: Planting crops that can withstand high salinity levels is crucial. Some salt-tolerant crops include barley, certain wheat varieties, and certain grasses.
vi. Applying Gypsum:Gypsum (calcium sulfate) can be applied to saline soil to help displace sodium ions and improve soil structure. It also reduces the harmful effects of sodium on soil permeability.
vii. Proper irrigation management: Proper, efficient irrigation practices should be followed in affected areas, like drip or sprinkler irrigation, to reduce further salinization by lowering the rate of water evaporation and runoff from the soil surface.
viii. Avoiding Over-fertilization: Excessive use of fertilizers can contribute to soil salinity. Proper fertilization practices based on soil nutrient tests help maintain a balanced nutrient profile.
ix. Mulching: Mulching with organic materials or cover crops helps conserve soil moisture, reduce soil temperature, and minimize salt accumulation at the soil surface.
x. Crop Rotation: Following a proper crop rotation and cultivating diverse crops in affected areas may help break the salt accumulation cycle in soil.
xi. Monitoring and Maintenance: Regular monitoring of soil salinity levels is essential to track progress and adjust management practices accordingly. It's an ongoing process that requires consistent maintenance and adaptation to changing conditions.

By combining these strategies and adapting them to the specific characteristics of the saline soil, effective management can gradually reduce salinity levels and improve soil health for sustainable agricultural production.

Earlier saline soils were ameliorated chemically by applying amendments like gypsum or sulphuric acid. Still,chemical costs have hiked so much in the last couple of years due to increased demand, making the amelioration process a costly affair through chemically [14]. The government has also reduced subsidies in some developed countries. An alternate way of reclamating saline land is phytoremediation, which cultivates salt-tolerant species. This could be an effective way to improve this situation [5] and maintain the sustainability of agricultural fields [15-17]. This might be an environmentally safe and clean technique thatdoes not burden the farmer's pocket much. They even provide other benefits in food, fodder, fuelwood, and industrial raw materials and increase the farmers' income possessing salt-affected lands. Several halophytic plant species have been tried in the past for their possible use in the reclamation of salt-affected soils [18-20]. After conducting experiments, several researchers found phytoremediation to be an effective amelioration strategy for calcareous saline-sodic and sodic soils.

In contrast to the chemical amelioration of sodic soils, phytoremediation is achieved by the ability of plant roots to increase the dissolution rate of calcite, thereby resulting in enhanced levels of Ca^{2+} in the soil solution to replace Na^{+} from the cation exchange complex effectively. Phytoremediation is advantageous in several aspects:

(1) There is no extra burden on the farmer's pocket for purchasing chemicals like gypsum to amend the soil,
(2) Obtaining other financial benefits from these salt-tolerant crops grown during sodic soil amelioration,
(3) Enhancing the soil aeration through macro pores and aggregate stability improves root proliferation and soil hydraulic properties,
(4) Improving root proliferation increases the availability of soil nutrients to plants,
(5) Excess and uniform area of soil depth for amelioration and
(6) Environmental gain of soil carbon through sequestration during and past amelioration process.

5. Phytoremediation

From ancient times, plants have been considered capable of adapting to diverse environmental and adverse conditions and altering the soil's physical and chemical properties, such as water retention capacity, pH, and nutritional properties. They can also remove excess salts from the soil [11]. Phytoremediation or vegetative bioremediation of salt-affected soils can be defined as cultivating salt-accumulating or salt-tolerant plants to reduce soil salinity.

Criteria for selection of plant species for phytoremediation

1. Select those potential plants thatcan sustain and withstand varying degrees of salinity of soil and water and can gain an average growth
2. Store a good quantity of salts from the affected soil
3. They should also have other market-oriented economic agricultural uses like food, fodder, fuel, etc.

Several plant species, including grasses, trees, and even some vegetables, were being taken to lessen saline land (Table 2); however, planting trees is more emphasized as they provide fodder fruits and wood for timber and fuel. Therefore, agroforestry models, including salt-tolerant trees and crops, might be an economical and viable approach for the remediation of salt-stressed lands.

Table 2 Salt-tolerant plant species for phytoremediation.

Vegetables	*Aster tripolium, Brassica napus, Trigonella foenum- graceum, Spinacea oleracea, Medicago falcate, Brassica carinata, Brassica juncea, Lactuca sativa, Brassica campestris, Eruca sativa, Coriandrum sativum*
Grasses	*Leptochloafusca, Sporobolus arabicus, Cynodondactylon, Hordeum vulgare, Sorghum vulgare, S. halepense, Panicum antidotale, P. maximum, Echinochloacrusgalli, E. colona, Polypogonmonspeliensis, Avena sativa, Lolium multiflorum, Desmostachyabipinnata*
Shrubs	*Suaeda fruticose, Kochia indica, Medicago sativa, Atriplex nummularia, Sesbania rostrate, Atriplex amnicola, Macroptiliumatropurpureum, Atriplex lentiformis, Trifolium resupinatum, Atriplex undulate, Atriplex crassifolia, Sesbania formosa, Beta vulgaris, Lotus carniculatus, Trifolium alexandrinum, Sesbania aculeate*
Trees	*Acacia acuminate,A adsurgens,A. ampliceps,A. bivenosa,A. cambagei, A. coriacea, A. cacia, A. cunnighamii, A. holosericea, A. nilotica, A. sclerosperma, A. saligna, A. validinervia, A. Victoria, Casuarina glauca, C. nemophila, C. obesa, C. sturtii, Eucalyptus microtheca, E striaticalyx, Prosopis cineraria, P. juliflora, P. tamarugo, P. calcicola, P. chilensis, Leucaena leucocephala*

Source- Ashraf et al., 2010 [16].

According to Flowers and Colmer [21], some plant species can survive and withstand salt concentrations of more than 20 dSm^{-1}. Such plant species are known as halophytes, around 1% of the world's flora. They can survive, grow well, and reproduce with enhanced salt concentration levels in soil with fresh water. These plant species have unique anatomical and morphological features like succulence, osmotic adjustment, ion compartmentalization, uptake and transport, redox potential, antioxidant systems, and salt inclusion or discharge for varying salt concentrations [22].

Cultivating these plant species in the salt-affected unused and marginal agricultural lands opens a new way for sustainable development.

These plants are classified into some groups based on their mechanism for salt tolerance [23]:

Excluder: These kinds of plants have roots with ultra-filtration mechanisms, which enable them to grow in salt-stress conditions. They are found mainly in mangrove vegetation. *e.g.*, *Rhizophora mucronata, Ceriopscandolleana, Bruguieragymnorrhiza, Kandeliacandel* etc.

Accumulators: These plants are succulent and collect high amounts of salt in their plant parts, tissues, and cells, thereby overcoming the excess salt conditions. e.g., *Sonneratia apetala, Sonneratiaacida, Sonneratia alba, Limnitzeraracemosa, Excoecariaagallocha, Salvadora persica, Sesuviumportulacastrum, Suaedanudiflora, and Pentatropissianshoides* etc.

Conductor: These plants adjust themselves by excreting excess salts in the air through their salt glands and salt levels. e.g., *Avicennia officinalis, Avicennia alba, Avicennia marina, Aegiceroscorniculatum, Acanthus ilicifolius* etc.

5.1 Mechanisms of Halophytes for Salt Removal

Phyto-accumulation: In this process, plants uptake high amounts of Na^+ and Cl^- salts from the soil and store them in their plant parts, especially in the shoot. e.g., *Cynodon dactylon* accumulates Na^+ and Cl^- salts in its salt gland, and *Thinopyrumper granulata* accumulates Na^+ and Cl^- salts in its cell (Figure 1).

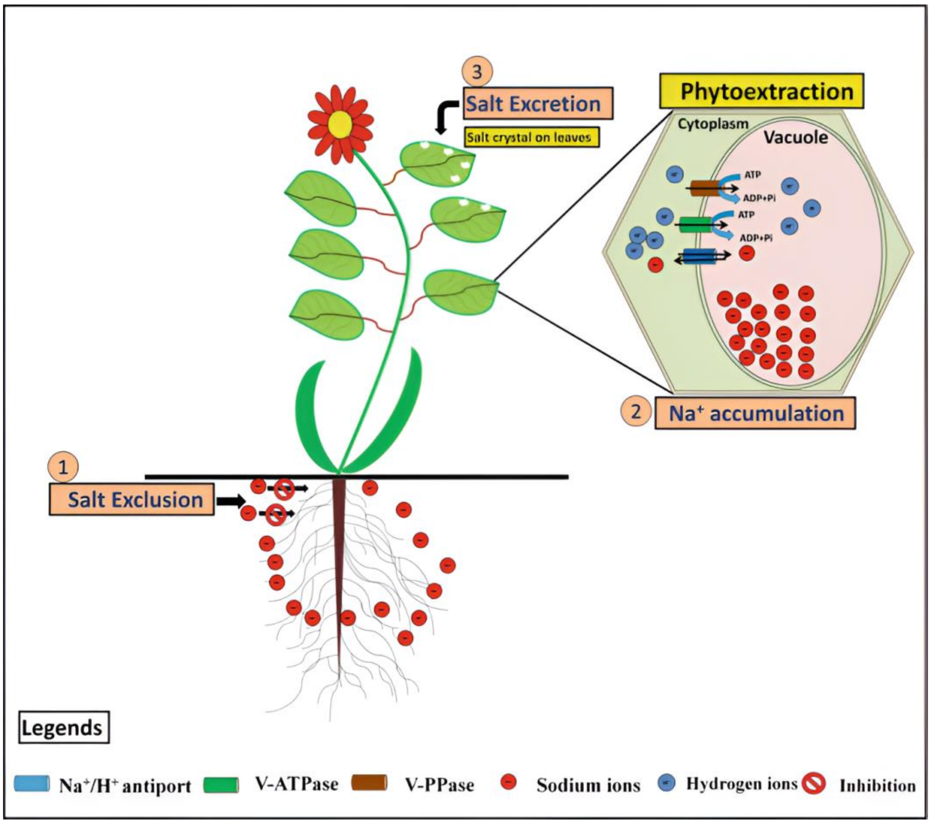

Figure 1 Desalination mechanism of halophytes. Source- Saddhe et al., 2010 [24].

Phyto stabilization: It involves the establishment of a plant cover on the salt-affected land. The main objective is accumulating the salts by roots and reducing their movement in the soil. For example, *Populus alba* can have more than 80% Na^+ salts in the root.

The process behind the immobilization of salts involves transpiration and rigorous and expanded root growth of the plant.

Phyto-transformation: This is the ability of plants to change the chemical composition of salts and sustain them in higher salt concentration conditions of the soil solution. The process involves the absorption of salt from higher concentrations and the breakdown of these salts in plant cells through many metabolic processes with the help of several enzymes produced by the plant. e.g., Periwinkle (*Catharanthus roseus*), Water thyme (*Hydrilla* spp.), Waterweed (*Elodea* spp.).

5.2 Changes in Soil Physio-Chemical Properties after Planting of Halophytes

Salt-tolerant plant species improve the soil's physical properties like improving aeration and water-holding capacity of soil with modification in porosity, structure stability, and bulk density of the soil [25], as the plant roots and their behavior are mainly responsible for changing the soil environment and structure [26, 27]. The deep root develops the macro pores and expels the trapped air from there [28]. It also helps exchange salt ions, mainly Na^+, with others from the deeper layer of soil during the remediation process.

In some studies, heavy and deep tillage operations were also found to beviable options for drilling to improve the dense and complexsubsoils. Some plant species can grow in compact soil and improve the soil, enhancing the macro pores and gaseous exchange with their robust and deep roots [29]. *Atriplex hortensis*, *Festuca arundinacea*, *Paspalum notatum*, and *Suaedafruiticosa* are some examples of plants that can grow on complexand compact soil layers and improve the soil's porosity with their deep and robust root system [5]. Some perennial deep-rooted grasses like Pennisetum and Cenchrus spp. have also shown a positive impact during remediation by enhancing the hydraulic properties of salt-affected soils. Akhter [30] also reported increased soil hydraulic permeability with five years of continuous Laptochloafusca (Kallar Grass) cultivation in saline land. Caron [31] also observed a significant improvement in soil aggregate stability by cultivating *Bromus madritensis* (Bromegrass) for three years.

These salt-tolerant crops also influence the soil's chemical properties like organic carbon, pH, sodium adsorption ratio (SAR), and electrical conductivity (EC) and improve the soil by enhancing the values of these parameters. Akhter [5] reported a 71% decline in salinity after cultivating Laptochloafusca for five years due to the leaching of salts in the deeper layer. Ashraf [32] also reported a gradual decrease in EC after three years of planting *Acacia nilotica* and *Atriplex lentiformis*. Additionally, the increase in organic matter contributed by the decomposition of plant parts like leaves, stems, etc., changes the soil quality and enhances microbial activity [33].

According to Malik [34], studies with *Laptochloafusca* reported a reduction in SAR values of theupper layer in saline soil and leaching of Na^+ salts to the lower layer. During the process, NH_4^+ uptake was also reduced, and a high concentration of H^+ lowers the soil pH. Shekhawat [35] worked on salt-tolerant plants such as saxaul or seksewil (*Haloxylonrecurvum*), see pweeds (*Suaedanudiflora*) and *Salsola baryosma* and found that they removed sodium (Na^+) 17, 15.6 and 9 g plant^{-1} respectively, during their growth period of three months. The presence of $CaCO_3$ in the deeper layer of sodic soil may also be affected by H_2CO_3 due to the higher solubility of $CaCO_3$ with H_2CO_3. Robbins [36] suggested that CO_2 released by plant roots during respiration is mainly responsible for rehabilitating saline soils. During the process, Ca^{2+}replaces Na^+ and other salts from the soil exchange sites. Thus, during the process, halophytes influence the main soil chemical properties, such as pH, ESP (exchangeable sodium percentage), and EC. Qadir and Oster [37] reported during a comparative study of phytoremediation with remediation of saline soil with chemicals that reducedsodicity by 52% through salt-tolerant plants compared to 62% reduction using gypsum. However, suppose irrigation water is provided to plants during the off-season, which is responsible for the leaching of sodium (Na^+) along with other anions such as Cl^-, HCO^{3-} and SO_4^{2-}hamper plant growth. In that case, phytoremediation may be an effective and more economical option for ameliorating saline wasteland.

6. Conclusion

Based on available literature and reports on phytoremediation by experts, it is suggested that ameliorating salt-affected soils through the production of salt-tolerant plants may be the most practical, cost-effective, and viable approach for sustainable utilization of saline lands, particularly for resource-poor and marginal farmers. These plants can be used for fodder, biofuel, industry, ornament, or food. In this way, domesticating these plants to crops is also a good choice [38]. As salt-tolerant plants used for phytoremediation add organic matter to the soil and other essential ions such as Ca^{2+}, K^+, N, and P, they increase the productivity of the soil, in addition to removing Cl^- and Na^+. However, the success of this approach dramatically depends on the understanding of salt-tolerant plant species, their potential to withstand and grow in varying salt levels of soil, and their commercial value.

Future research in the phytoremediation of saline soils promises to transform unproductive lands into fertile and sustainable ecosystems. By advancing the understanding of plant biology, soil science, and microbial ecologyand developing innovative, integrative remediation strategies, we can create practicalsolutions to mitigate soil salinity. These efforts will contribute significantly to global food security, environmental sustainability, and the resilience of agricultural systems to climate change.

Acknowledgments

We express our gratitude to The Director, CSIR-NBRI, Lucknow for providing time to time unconditional and essential support and guidance for the research work.

Author Contributions

R.C. Nainwal: Conceptualization, Writing- Original draft preparation. P. Chaurasiya.: Supervised, Reviewed, and Corrected the Original draft. A. Kumar: Manuscript Writing and Editing. Mohan Singh: Manuscript writing. Devendra Singh: Reviewed the draft. S. K. Tewari: Supervised, Reviewed and Corrected the Original draft.

Competing Interests

The authors have declared that no competing interests exist.

References

1. International Center for Agricultural Research in the Dry Areas. Marginal quality water: A solution to fresh water scarcity.Aleppo, Syria: International Center for Agricultural Research in the Dry Areas; 2002.
2. Szabolcs I. Soils and salinisation. In: Handbook of plant and crop stress. New York, NY: Marcel Dekker; 1994. pp. 3-11.
3. Ghassemi F, Jakeman AJ, Nix HA. Salinisation of land and water resources: Human causes, extent, management and case studies. Warlingford, UK:CABI Publishing; 1995.
4. Cheraghi SA. Institutional and scientific profiles of organizations working on saline agriculture in Iran. Prospects of saline agriculture in the Arabian Peninsula: Proceedings of the

International Seminar on Prospects of Saline Agriculture in the GCC Countries; 2001March 18-20; Dubai, United Arab Emirates. Amherst, MA:Amherst Scientific Publishers.
5. Akhter J, Mahmood K, Malik KA, Ahmed S, Murray R. Amelioration of a saline sodic soil through cultivation of a salt-tolerant grass Leptochloafusca. Environ Conserv. 2003;30:168-174.
6. Mukhopadhyay R, Sarkar B, Jat HS, Sharma PC, Bolan NS. Soil salinity under climate change: Challenges for sustainable agriculture and food security. J Environ Manage. 2021;280:111736.
7. Trabelsi L, Gargouri K, Hassena AB, Mbadra C, Ghrab M, Ncube B, et al. Impact of drought and salinity on olive water status and physiological performance in an arid climate. Agric Water Manage. 2019;213:749-759.
8. Glenn E, Hicks N, Riley J, Swingle S. Seawater irrigation of halophytes for animal feed. In: Halophytes and biosalineagriculture. Boca Raton, FL: CRC Press; 1995. pp. 221-236.
9. Kumar P, Sharma PK. Soil salinity and food security in India. Front Sustain Food Syst. 2020;4:533781.
10. Mandal S, Raju R, Kumar A, Kumar P, Sharma PC. Current status of research, technology response and policy needs of salt-affected soils in India-a review. J Indian Soc Coast Agric Res. 2018;36: 40-53.
11. Naorem A, Jayaraman S, Dang YP, Dalal RC, Sinha NK, Rao CS, et al. Soil constraints in an arid environment-challenges, prospects, and implications. Agronomy. 2023;13:220.
12. Bolan N, Srivastava P, Rao CS, Satyanaraya PV, Anderson GC, Bolan S, et al. Distribution, characteristics and management of calcareous soils. Adv Agron. 2023; 182: 81-130.
13. Qadir M, Oster JD, Schubert S, Noble AD, Sahrawat KL. Phytoremediation of sodic and saline-sodic soils. Adv Agron. 2007;96:197-247.
14. Rabhi M, Talbi O, Atia A, Abdelly C, Smaoui A. Selection of a halophyte that could be used in the bioreclamation of salt-affected soils in arid and semi-arid regions. In: Biosaline agriculture and high salinity tolerance.Basel, Switzerland: Birkhäuser Basel; 2008. pp. 241-246.
15. Abrol IP, Yadav JS, Massoud FI. Salt-affected soils and their management. Rome, Italy: Food and Agriculture Organization; 1988.
16. Ashraf MY, Ashraf M, Mahmood K, Akhter J, Hussain F, Arshad M. Phytoremediation of saline soils for sustainable agricultural productivity. In: Plant adaptation and phytoremediation. Dordrecht, Netherlands: Springer; 2010. pp. 335-355.
17. Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP, Balasubramanian T. Restoration of saline land by halophytes for Indian soils. Soil Biol Biochem. 2007;39:2661-2664.
18. De Villiers AJ, Van Rooyen MW, Theron GK, Claassens AS. Removal of sodium and chloride from a saline soil by Mesembryanthemum barklyi. J Arid Environ. 1995;29:325-330.
19. Gul B, Weber DJ, Khan MA. Effect of salinity and planting density on physiological responses of Allenrolfea occidentals. West N Am Nat. 2000; 60: 188-197.
20. Jithesh MN, Prashanth SR, Sivaprakash KR, Parida A. Monitoring expression profiles of antioxidant genes to salinity, iron, oxidative, light and hyperosmotic stresses in the highly salt tolerant grey mangrove, Avicennia marina (Forsk.) Vierh. by mRNA analysis. Plant Cell Rep. 2006;25:865-876.
21. Flowers TJ, Colmer TD. Plant salt tolerance: Adaptations in halophytes. Ann Bot. 2015;115:327-331.

22. Lokhande VH, Suprasanna P. Prospects of halophytes in understanding and managing abiotic stress tolerance. In: Environmental adaptations and stress tolerance of plants in the era of climate change. New York, NY: Springer; 2012. pp. 29-56.
23. Walter H. Salinity problems in the acid zones. The adaptations of plants to saline soils. Arid Zone Res. 1961;14: 65-68.
24. Saddhe AA, Manuka R, Nikalje GC, Penna S. Halophytes as a potential resource for phytodesalination. In: Handbook of halophytes: From molecules to ecosystems towards biosalineagriculture. Cham: Springer; 2020. pp. 1-21.
25. Marschner H. Marschner's mineral nutrition of higher plants. London, UK: Academic press; 1995.
26. Czarnes S, Hallett PD, Bengough AG, Young IM. Root-and microbial-derived mucilages affect soil structure and water transport. Eur J Soil Sci. 2000;51:435-443.
27. Yunusa IA, Newton PJ. Plants for amelioration of subsoil constraints and hydrological control: The primer-plant concept. Plant Soil. 2003;257:261-281.
28. Tisdall JM. Fungal hyphae and structural stability of soil. Soil Res. 1991;29:729-743.
29. Ashraf MY, Shirazi MU, Ashraf M, Sarwar G, Khan MA. Utilization of salt-affected soils by growing some Acacia species. In: Ecophysiology of high salinity tolerant plants. Dordrecht, Netherlands: Springer; 2006. pp. 289-311.
30. Akhter J, Murray R, Mahmood K, Malik KA, Ahmed S. Improvement of degraded physical properties of a saline-sodic soil by reclamation with kallar grass (Leptochloafusca). Plant Soil. 2004;258:207-216.
31. Caron J, Kay BD, Stone JA. Improvement of structural stability of a clay loam with drying. Soil Sci Soc Am J. 1992;56:1583-1590.
32. Ashraf MY, Sarwar G, Ashraf M, Hussain F, Wahed RA, Iqbal MM. Growth performance and nutritional value of salt tolerant plants growing under saline environments. In: Biosaline agriculture and salinity tolerance in plants.Basel, Switzerland: Birkhäuser Basel; 2006. pp. 35-44.
33. Dormaar JF. Effect of plant roots on chemical and biochemical properties of surrounding discrete soil zones. Can J Soil Sci. 1988;68:233-242.
34. Malik KA. Prospects for saline agriculture in Pakistan: Today and tomorrow. In: Prospects for Saline Agriculture. Dordrecht, Netherlands: Springer; 2002. pp. 1-6.
35. Shekhawat VP, Kumar A, Neumann KH. Bio-reclamation of secondary salinized soils using halophytes. In: Biosaline agriculture and salinity tolerance in plants.Dordrecht, Netherlands: Springer; 2006. pp. 147-154.
36. Robbins CW. Sodic calcareous soil reclamation as affected by different amendments and crops 1. Agron J. 1986;78:916-920.
37. Qadir M, Oster JD. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. Sci Total Environ. 2004;323:1-19.
38. Xu C, Tang X, Shao H, Wang H. Salinity tolerance mechanism of economic halophytes from physiological to molecular hierarchy for improving food quality. Curr Genomics. 2016;17:207-214.