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Soil salinity: Recent advances and future prospects

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Abstract

Soil salinity is one of the major environmental constraints limiting agricultural productivity and global food security, affecting approximately 833 M ha of land worldwide. Its extent is increasing due to climate change, seawater intrusion, rock weathering, poor irrigation practices, inadequate drainage, groundwater over-extraction, excessive fertiliser use, irrigation with saline water and industrial effluent discharge. Salinity degrades soil structure, reduces nutrient availability, impairs photosynthesis, restricts plant growth and ultimately decreases crop productivity. This review provides a comprehensive and up-to-date synthesis of the causes, impacts, assessment methods and management strategies for soil salinity while highlighting recent advances in biotechnology and precision agriculture. Unlike previous reviews that focus on individual aspects of salinity, this review integrates conventional and emerging approaches within a single framework. Relevant literature was systematically identified and screened using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure transparent and comprehensive coverage. Recent advances in salinity assessment include remote sensing, electromagnetic induction (EMI), machine learning and geospatial techniques, enabling accurate large-scale monitoring and management of salt-affected soils. Effective mitigation strategies include improved irrigation and drainage, mulching, chemical amendments, silicon (Si) application, beneficial microorganisms, phytoremediation, nanotechnology and integrated soil management. Biotechnological approaches such as marker-assisted breeding, molecular breeding and CRISPR/Cas9 gene editing have accelerated the development of salt-tolerant crop varieties, including BRRI dhan73, BRRI dhan99, CSR 101 and CSR 104. Future research should prioritise climate-resilient agriculture, sustainable land reclamation, precision farming and artificial intelligence (AI)-driven technologies to enhance long-term salinity management and food security.

Keywords: biotechnology; CRISPR/Cas9; phytoremediation; remote sensing; salinity management; salt-affected soils; soil salinity

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1. Introduction

Soil salinity is one of the environmental constraints limiting agricultural productivity globally. Soil salinity is the concentration of soluble salts in the soil water and it is determined through the electrical conductivity (EC) test (1). Globally, there are 833 M ha of salinised lands, representing 8.7 % of the global land surface. The soil salinisation process takes place across all continents, especially in dry and semi-dry conditions. Approximately 1.5 M ha of arable land are lost per year due to soil salinisation (2). There are 6.72–6.74 M ha of salt-affected soils in India that constitute 2.1 % of the total geographical area. Out of these, there are 2.95 M ha of saline soils and 3.77 M ha of sodic soils in the country. It is reported that 13231 ha of land in Tamil Nadu are salt-affected (3, 4). Geological processes like formation of rocks, weathering of rocks and seawater intrusion are some of the natural causes of soil salinisation. However, anthropogenic activities also contribute significantly to this process. Soil salinity has been increased by anthropogenic factors like improper irrigation practices, excessive fertilisation and the absence of adequate drainage systems (5).

Even low levels of soil salinity (< 4 dS m^{-1}) induce physiological stress in plants by altering osmotic potential, causing ion toxicity (Na^+ and Cl^-) and reducing photosynthetic efficiency through decreased stomatal conductance (6). Securing food production for a growing global population amidst intensifying soil salinity challenges has driven accelerated research into soil salinity and the development of practices that can help mitigate the problem at the farm level (7). Although several reviews have addressed individual aspects of soil salinity, recent advances in remote sensing, artificial intelligence (AI), precision agriculture, nanotechnology, beneficial microorganisms and genome editing have not

been comprehensively synthesised within a single review. An updated evaluation is therefore warranted.

This review integrates recent developments in salinity assessment, sustainable management, biotechnology and climate-resilient agriculture published between 2010 and 2025. This study primarily focused on individual aspects of soil salinity, whereas recent advances in assessment technologies, sustainable management and biotechnology warrant a comprehensive and updated synthesis (5, 8, 9).

2. Materials and Methods

Literature search strategy

A comprehensive literature search was conducted using the Scopus, Web of Science, ScienceDirect, Google Scholar and SpringerLink databases. Studies published between 2010 and 2025 containing keywords such as soil salinity, salt-affected soils, soil salinity evaluation, remote sensing, soil restoration, phytoremediation, biochar, halotolerant microbes, nanotechnology, CRISPR/Cas9 and salt-tolerant crops were chosen. Peer-reviewed research articles, review papers, books and authoritative reports published in English were included, whereas conference abstracts, duplicate records, non-peer-reviewed publications and studies unrelated to soil salinity were excluded. Duplicate records were removed before screening and the titles, abstracts and full texts of the remaining studies were assessed for eligibility according to the predefined inclusion and exclusion criteria. The literature selection followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A total of 420 records were identified through database searching, of which 80 duplicate records were removed. The remaining 340 records were screened based on titles and abstracts, 110 full-text articles were assessed for eligibility and 69 studies meeting the predefined inclusion criteria were finally included in this review, as illustrated in Fig. 1.

Causes of salinity

Drylands are especially characterised by the common processes of soil salinisation. Both natural and anthropogenic factors drive these processes. The latter are primarily associated with agricultural land use, particularly irrigated agriculture, whereas natural causes include elements like climate, lithology, terrain and pedology (10).

Natural causes

Soluble cations and anions are released during the weathering of rocks and minerals. The most prevalent cations are calcium ion (Ca^{2+}), potassium ion (K^{+}), magnesium ion (Mg^{2+}) and sodium ion (Na^{+}), whereas the predominant anions include bicarbonate ion (HCO_3^{-}), chloride ion (Cl^{-}) and sulfate ion (SO_4^{2-}). Certain rocks and minerals release these ions more readily than others, making them highly susceptible to chemical weathering and natural salinisation (11). Secondary volcanic activities, such as fumaroles and thermal springs, also contribute chlorine and sulphur-rich compounds that increase the salinity of groundwater and soils (12). Coastal regions, particularly those in arid and semi-arid climates, are highly vulnerable to primary soil salinisation due to the deposition of marine salts through sea spray and aeolian transport (13). In addition, capillary rise of saline groundwater in areas with shallow water tables transports dissolved salts to the soil surface, where they accumulate following evaporation (14). Climatic conditions characterised by low rainfall and high evapotranspiration limit natural salt leaching and promote salt accumulation in the root zone, while closed drainage basins and poor natural drainage further intensify soil salinisation (15).

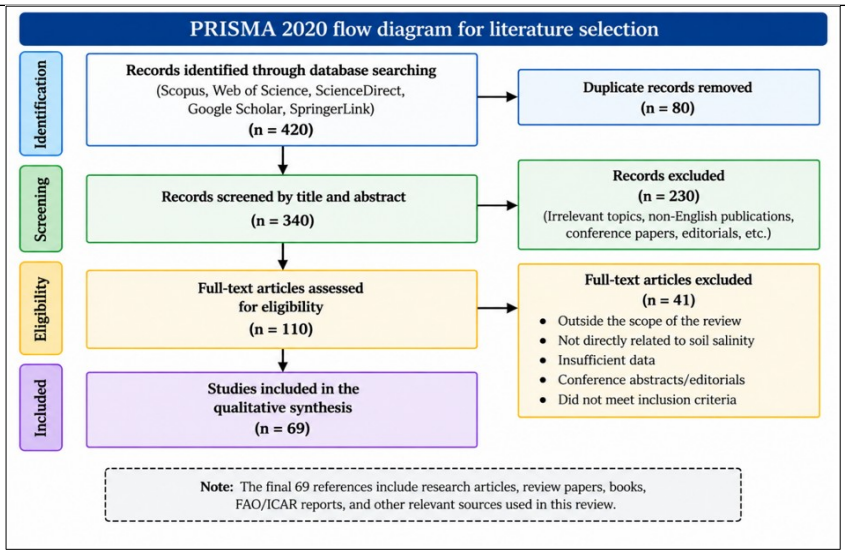


Fig. 1. PRISMA 2020 flow diagram illustrating the literature search and study selection process used in this review.
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses;
FAO/ICAR: Food and Agriculture Organization (FAO)/ Indian Council of Agricultural Research.

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Anthropogenic causes

Waterlogging and irrigation lacking adequate drainage represent the primary drivers of secondary soil salinisation. These conditions leave dissolved salts on the ground's surface or in the soil profile (10). The salt concentration in river water increases downstream as drainage water and groundwater from agricultural lands flow into rivers. Consequently, utilising this downstream water for crop irrigation exacerbates the risk of soil salinisation (14). Although drip and sprinkler irrigation improve water-use efficiency, inadequate leaching under these systems may result in localised salt accumulation within the root (15). In addition to inappropriate irrigation practices, several other anthropogenic activities contribute significantly to soil salinisation. Over-extraction of groundwater can induce seawater intrusion in coastal aquifers and increase the upward movement of saline groundwater through capillary rise, resulting in salt accumulation in the root zone. The use of saline or poor-quality irrigation water and excessive application of chemical fertilisers further accelerate the buildup of soluble salts, particularly in arid and semi-arid regions where natural leaching is limited (16–18). Furthermore, land clearing, rising groundwater tables, rapid urbanisation and the discharge of untreated or inadequately treated industrial effluents can degrade soil quality by increasing salt accumulation and altering the natural hydrological balance (16, 17, 19). Collectively, these anthropogenic activities intensify secondary salinisation and highlight the need for sustainable land and water management practices (17–19).

Impacts of soil salinity

Long-term use of saline water for irrigation results in significant alterations in the physico-chemical characteristics of the soil with respect to EC, exchangeable sodium percentage (ESP), pH, density, decrease in K exchange capacity, aggregate stability, hydraulic conductivity and available water. The greater soil salinity results in poor soil structure and water-holding capability (20). Most crop plants are susceptible to salinity, which is caused by high concentrations of salts in the soil and because the area of land impacted by salinity is growing daily, salinity is one of the harshest environmental variables affecting crop plant productivity. Yield reductions of 20–50 % have been reported in many major crops under moderate to severe salinity stress, depending on crop species, growth stage and salinity intensity. These losses are expected to intensify under climate change due to increasing drought frequency, higher evapotranspiration and expanding salinisation of irrigated lands (21).

Advances in assessment and monitoring of soil salinity

Traditional soil salinity assessment based on field EC measurements has evolved toward integrated approaches combining remote sensing, geospatial analysis and machine learning to enable rapid, large-scale and cost-effective monitoring of salt-affected soils. The use of multi-source satellite data with environmental variables enables high-resolution mapping, while models such as random forest (RF) improve prediction accuracy (R^2 up to 0.85–0.87). Radar data are more effective in humid regions, whereas optical data perform better in arid areas, providing a reliable framework for large-scale salinity monitoring (21). Improved spatial, temporal and spectral resolutions have enhanced the detection of salinity dynamics across regional and landscape scales. Additionally, ground-based systems such as electromagnetic induction (EMI) instruments provide rapid, non-destructive measurements of the soil's apparent EC by generating a primary electromagnetic field that induces electrical currents in the subsurface. The resulting secondary electromagnetic field is measured to estimate spatial variations in soil salinity. When integrated with geospatial data, EMI enables accurate assessment of salinisation at both local and field scales, providing policymakers and land managers with a more comprehensive understanding of the spatial dynamics of salinity for site-specific management and reclamation planning (22). Several recent studies have demonstrated that salinisation mapping can be greatly enhanced by combining remote sensing data with strong analytical methods. A study conducted in the Qom Valley of Iraq demonstrated that soil salinity can be precisely predicted and mapped using Landsat 8 OLI spectral indices combined with topographic features (22). Another study used 241 soil salinity samples and Landsat OLI imagery to assess soil salinity in Bangladesh's southwestern coastal region. Three machine learning models-RF, bagging with RF and artificial neural network (ANN) were used to develop and assess thirteen salinity indices. The ANN model outperformed the others in terms of prediction accuracy (area under the curve (AUC) = 0.921). The area was divided into five salinity zones by the generated salinity map, with high salinity zones occupying the largest percentage, followed by moderate and low salinity zones. This work offers valuable insights for sustainable coastal management and agricultural planning and it indicates the efficiency of remote sensing and machine learning for assessing soil salinity (23).

Recent advances in soil salinity assessment include the use of EMI and inversion modelling for three-dimensional (3D) salinity mapping. These techniques provide rapid, non-destructive and cost-effective estimation of soil salinity distribution across different soil depths. Studies have shown that continuous subsurface drainage (SSD) effectively reduces salinity and spatial variability, while higher salt accumulation is often observed in deeper soil layers due to leaching processes. Such approaches improve precision land and drainage management for sustainable reclamation of salt-affected soils (24).

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Techniques such as thermal and multispectral satellite imagery, combined with models like RF, enable large-scale and high-resolution salinity mapping, though challenges like data limitations and spatial variability remain (25). There are many challenges that come with remote sensing soil salinity mapping such as limited spatial and temporal data availability. Accuracy in measuring soil salinity may be hindered by various issues such as dense vegetation cover, cloud coverage and spatially heterogeneous soil salt concentrations. Despite providing more details about the soil, hyperspectral imaging suffers from the limitation of being expensive and inaccessible. There are some challenges with ground validation, especially because soils are highly variable. Furthermore, processing multi-source datasets demands substantial computational power. Future developments integrating hyperspectral imagery, unmanned aerial vehicles (UAVs), Internet of Things (IoT) sensors and AI are expected to further improve the accuracy and operational efficiency of soil salinity monitoring (26).

Advances in soil salinity management

Soil salinity management has evolved from conventional reclamation practices to integrated approaches that combine agronomic, chemical, biological and advanced technological interventions. The integration of these complementary strategies provides a more sustainable approach for improving soil health and crop productivity under saline conditions. Fig. 2 presents an overview of the major soil salinity management strategies discussed in this review.

Agronomic approach

Irrigation management: Proper irrigation and crop management are crucial for preventing salt buildup and addressing water scarcity in dry land environments (27). A combination of saline and high-quality water was used to reduce irrigation water salinity during pearl millet cultivation and the yields of the AVKB-19 and ICMV-15111 varieties grown under saline soil conditions were compared (28). Similarly, maize grown under drip fertigation with good-quality irrigation water and the recommended fertiliser dose produced the highest yield and nutrient uptake (29). Alternating fresh and saline water (EC 4 dS m^{-1}) effectively reduced salinity stress and improved nutrient use efficiency, whereas continuous saline irrigation without fertilisers increased soil EC and reduced crop performance and soil nutrient availability (29).

Drainage management: The process of agricultural drainage becomes important for maintaining an appropriate groundwater level through draining out excess water in the soil profile due to rainfall as well as removal of salts that dissolve in the root zone. Subsurface drainage is a critical mechanism for leaching accumulated salts from depths up to 1.5 m below the soil surface. For the reclamation of saline soils, two types of SSD can be helpful: (i) horizontal SSD, which involves a network of drains made up of the main drain, lateral drains and collectors and works up to 1.5–2.0 m depth of root zone (30); and (ii) vertical SSD, which is related to pumping excess water by tube well (31). A comparative study of free drainage (FD) and controlled drainage (CD) systems in waterlogged saline Vertisols showed that FD achieved faster soil reclamation, whereas CD significantly conserved irrigation water and reduced drainage discharge and nitrate losses. Although slightly less effective in salt leaching, the CD system maintained favourable economic returns and proved to be a sustainable option for improving water and nutrient management in salt-affected areas with limited water availability (32).

Mulching management: The mulching of soil helps in saving soil moisture content, suppresses evaporative losses and reduces soil salinity. The prolonged retention of soil moisture can result in lowering soil salinity and increase nutrient uptake, plant growth and yield (33, 34). Paddy straw mulch with farm yard manure (FYM: 7.5 Mg ha^{-1}) and vermicompost (2.5 Mg ha^{-1}) resulted in maximum fruit yield of brinjal and benefit-cost ratio (35). In addition to conventional organic mulches, biodegradable mulches, crop residue mulches and biochar-amended mulches have emerged as sustainable alternatives for salinity management. These mulching materials improve soil moisture retention, moderate soil temperature, reduce surface salt accumulation, enhance microbial activity and increase soil organic carbon, thereby improving crop performance under saline conditions. The integration of mulching with efficient irrigation and nutrient management practices further enhances water-use efficiency and contributes to the sustainable reclamation of salt-affected soils (36, 37).

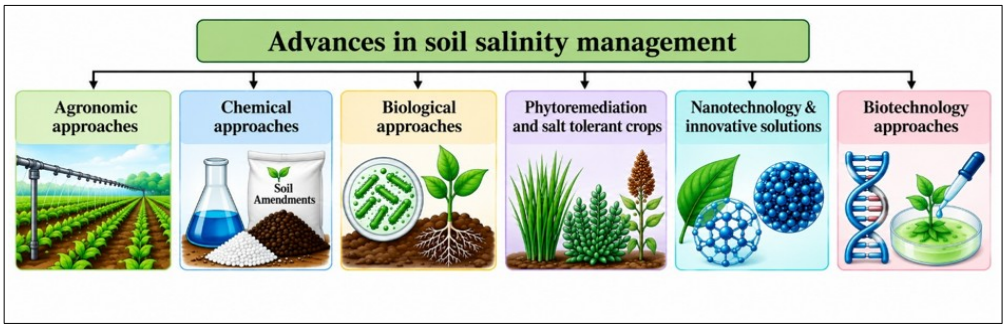


Fig. 2. Integrated approaches and recent advances in soil salinity management.

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Chemical approaches

Foliar spray of salicylic acid improved the salinity tolerance of sorghum by improving the physiological and biochemical defence system. Salicylic acid promotes the production of proline and antioxidant enzymes and thereby protects the photosynthesis machinery. It also plays a significant role in maintaining ion homeostasis through enhancement of K^+/Na^+ ratio. Among the tested concentrations, 250 mg L^{-1} was the most effective in reducing salinity-induced damage (38). Application of biochar, either alone or in combination with poultry manure compost, has emerged as an effective amendment for reducing soil salinity and improving soil properties. A significant reduction in the EC of the saturated soil extract (ECe) in saline-sodic soils was observed following the combined application of biochar and poultry manure compost (39).

Silicon (Si) is considered a beneficial element by the International Plant Nutrition Institute (IPNI) due to its role in plants during stress (40). The use of Si was able to effectively reduce the adverse effects of salinity on wheat by ensuring increased photosynthetic pigment levels, relative water content, protein and carbohydrate levels in the presence of salinity. The use of Si was also able to reduce lipid peroxidation, electrolyte leakage and oxidative stress, while upregulating the activity of antioxidant enzymes. The benefits of Si supplementation were more pronounced under severe salinity stress, particularly in the salt-sensitive wheat cultivar WH-1105 (41).

Biological approaches

Under salt stress, halophilic bacteria can absorb salt ions via bioaccumulation processes (42). The application of inoculated microorganisms reduced Na^+ concentrations in soil by increasing the abundance of microorganisms possessing Na^+/H^+, Na^+/Ca^{2+} and Na^+/K^+ transport proteins. This microbially mediated ion exchange significantly reduced soil salinity (43).

The use of oxalic acid functionalised biochar and halotolerant plant growth-promoting rhizobacteria (PGPR) was very beneficial for wheat growth as well as the improvement of soil in case of coastal saline-alkali soil. The biochar acted as a protective matrix, which helped in enhancing the viability of bacteria and their activity, thus leading to increased height, chlorophyll and biomass of plants. Moreover, the application of this method lowered the pH and Na adsorption ratio of soil, thus improving soil organic matter and the presence of microbes like *Bacillus*. Furthermore, the antioxidant enzyme activity was also enhanced due to this technique and oxidative stress was minimised, demonstrating better tolerance of plants against salinity (44).

Salt-tolerant plants enhance plant growth under saline conditions by enriching beneficial soil microorganisms through the release of organic acids and enzymes. Halophytes serve as valuable sources for isolating halotolerant PGPR possessing beneficial traits such as indole-3-acetic acid (IAA) production, phosphate solubilisation, siderophore production, nitrogen fixation, 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity and phytopathogen suppression (45). Inoculating crops with halotolerant PGPRs can promote sustainable crop production in salinity-based agriculture, including arid and semi-arid regions (46). Recent evidence suggests that combining PGPR with organic amendments produces greater improvements in soil quality and crop performance than microbial inoculation alone.

In addition to PGPR, other beneficial microorganisms such as arbuscular mycorrhizal fungi (AMF), endophytic fungi and cyanobacteria have shown considerable potential in alleviating salt stress and improving soil health (47–49). Arbuscular mycorrhizal fungi enhance nutrient and water uptake, improve soil aggregation, regulate ionic balance and strengthen antioxidant defence systems, thereby increasing plant tolerance to salinity (47). Endophytic fungi establish symbiotic associations within plant tissues and enhance plant growth by improving osmotic adjustment, nutrient acquisition, phytohormone production and antioxidant activity under saline conditions (48). Similarly, cyanobacteria contribute to soil fertility through biological nitrogen fixation, exopolysaccharide production and improvement of soil structure while enhancing microbial diversity and reducing the adverse effects of salt stress (49). The combined application of these beneficial microorganisms with PGPR and organic amendments represents a promising and sustainable biological strategy for the restoration and productive utilisation of salt-affected soils (50).

Phytoremediation strategies and salt-tolerant crops

Phytoremediation, which is referred to as vegetational bioremediation that involves cultivation of halophyte plants, used for improving salty land by reducing salinity of soil. In phytoremediation, plants that have grown well in various soil and water salinity levels are the ones that absorb large quantities of salts; hence, such plants should be used for providing extra income. These plants may be used as fuel, food, timber or fodder. Trees are better as they help improve soil quality and provide timber and fodder. Therefore, agroforestry systems integrating salt-tolerant trees and crops are considered as an effective and economical strategy for reclaiming saline soils (51). Different categories of salt-tolerant plants have been used for the reclamation of saline soils. Their applications in food production, fodder supply, agroforestry and soil improvement are summarised in Table 1.

These plant species have unique anatomical and morphological features like succulence, osmotic adjustment, ion compartmentalisation, uptake and transport, redox potential, antioxidant systems and salt inclusion or discharge for varying salt concentrations (53).

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Table 1. Important salt-tolerant plants for phytoremediation of saline soils (52)

Category	Important salt-tolerant plant species used in phytoremediation	Major uses
Vegetables	*Brassica juncea* (L.) Czern., *Brassica napus* (L.), *Spinacia oleracea* (L.), *Lactuca sativa* (L.), *Coriandrum sativum* (L.) and *Trigonella foenum-graecum* (L.)	Food and vegetable production
Grasses	*Cynodon dactylon* (L.) Pers., *Hordeum vulgare* L., *Sorghum vulgare* (L.) Pers., *Panicum maximum* Jacq., *Avena sativa* L. and *Lolium multiflorum* Lam.	Fodder, soil stabilisation and biomass production
Shrubs	*Atriplex nummularia* Lindl., *Atriplex lentiformis* (Torr.) S. Wats., *Kochia indica* Wight, *Suaeda fruticose* (Forssk.) Gmel., *Sesbania rostrata* Bremek. & Oberm. and *Medicago sativa* L.	Fodder, salt accumulation and soil reclamation
Trees	*Acacia nilotica* (L.) Delile, *Prosopis juliflora* (Sw.) DC., *Prosopis cineraria* (L.) Druce, *Eucalyptus microtheca* F.Muell., *Casuarina glauca* Sieber ex Spreng. and *Leucaena leucocephala* (Lam.) de Wit	Timber, fuel wood, fodder and agroforestry applications

In the Bizerte Lagoon zone, a field experiment was conducted using garden orache (*Atriplex hortensis* (L.)), a salt-tolerant halophyte used for saline soil rehabilitation. The photosynthetic activity and biomass of this plant decreased with increasing salinity levels; however, the plant maintained a relatively high relative water content. Soil EC decreased by 35 %, revealing the phytodesalination potential of garden orache for saline soils in arid and semi-arid regions (9).

Nanotechnology and innovative solutions

Nano-management of soil salinity can promote plant development, resistance to salt stress and soil structure/quality (8, 54). Such processes may include the use of traditional nanomaterials (such as gypsum, hydroxyapatite, sulfur), nano-nutrients (such as ca, selenium, Si, zinc oxide), nano-amendments (such as charcoal, compost and chitosan) and nano-halophyte (55). The carbon nanomaterials such as carbon nano-tubes, nanodots, nanographene and nanofullerene have been used for their property to provide protection from stress to crops. Green nano-Si (from maize wastes-150 and 300 mg L^{-1}) increased productivity and quality of fruits of Williams banana (*Musa* spp.) grown on saline irrigation water (EC 4.12 dS m^{-1}) on sandy soils and dry climatic conditions thus increasing antioxidants, proline and soluble carbohydrates accumulation (56). Green titanium dioxide (TiO_2) nanoparticles (30 and 50 ppm) enhanced germination, vigour indices and reduced oxidative stress in soybean (*Glycine max* L. var. 22 and 35) seedlings exposed to sodium chloride (NaCl) salinity levels ranging from 25–200 mM under sterilised sawdust conditions (57). Numerous nano-amendments including inorganic ones such as nano-selenium, nano-Si, nano-gypsum and nano-hydroxyapatite, as well as organic ones like nano-compost, nanobiochar and nano-chitosan have been shown to be effective in reducing soil salinity (58, 59). Biochar's nanoscale particle size improves its specific surface area and cation exchange capacity (CEC), making it a more effective soil supplement (60, 61). This can minimise detrimental ions in the rhizosphere, protect plants from salt stress, increase negative charge and promote adsorption of cations like Na^+ in saline soil (62, 63). In a previous study, it is found that Si nanoparticle-based biochar (2.5 % Si-BC) reduced salinity stress in wheat by improving growth, chlorophyll content, water status, antioxidant activity and nutrient uptake while reducing Na^+ and Cl^- accumulation (64).

Biotechnological tools for salt tolerance in soils

Conventional breeding, molecular breeding and marker-assisted selection helps in the identification and transfer of salt-tolerance traits in crops having high productivity. The genetic engineering and genome editing technology, like CRISPR/Cas9, increases salinity tolerance in plants through modification in the genes responsible for ion transport, osmoregulation, antioxidants production and stress signal transduction pathway. The recent advancements in CRISPR/Cas9 technology show its efficiency in increasing salinity tolerance in crops. In tomato, deletion of the negative regulatory domains of the SlHyPRP1 gene that enhanced salt tolerance during germination and vegetative growth stages. In rice, knockout of the OsbHLH024 gene increased the expression of ion transporter genes such as OsHKT1;3, OsHAK7 and OsSOS1 thereby promoting salt tolerance. Similarly, CRISPR/Cas9-mediated mutation of genes including OsRR22, OsRAV2, OsDST, OsNAC041 and OsmiR535 significantly improved the ability of rice plants to survive under saline conditions without affecting important agronomic traits. Gene editing approaches have also improved salt stress resistance in barley through HvITPK1 mutation and in tomato by modification of the SlARF4 gene (65).

Genes from wild halophytes are regarded as gene pools for salt tolerance traits which will be bred into crop plants for food security in salty regions. There is great potential in enhancing the salt tolerance of crop plants through introgressive breeding, domestication of wild relatives and other biotechnological approaches such as genome editing through CRISPR/Cas9 via genes of crop wild relatives (CWR). The chosen CWR cultivars of *Oryza alta* Swallen, *Solanum pimpinellifolium* L., *Solanum bigelovii* Torr., *Atriplex nummularia* Lindl. and *Leptochloa fusca* (L.) Kunth can be potential candidates for forage, food and energy crops in saline environments. However, challenges such as low yield, poor seed quality, high salt accumulation and maintenance of salinity tolerance during domestication should be carefully considered for successful crop development (66).

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Bangladesh has released several salt-tolerant rice varieties for saline prone areas. The BRRI dhan47 showed high tolerance up to 12–14 dS m^{-1} with good yield performance. Varieties such as BRRI dhan61 and BRRI dhan67 were developed for moderate saline conditions during Boro and vegetative stages. The BRRI dhan73 was developed using marker-assisted backcross breeding (MABC) by transferring the Saltol QTL from FL478 into BRRI dhan28, improving salinity tolerance and yield under stress. Recently released varieties BRRI dhan78, BRRI dhan97 and BRRI dhan99 exhibit tolerance to 8–10 dS m^{-1}, with BRRI dhan78 also showing submergence tolerance. Molecular studies have identified multiple salt-tolerance QTLs/genes in BRRI dhan97 and BRRI dhan99, thereby improving their adaptability to saline environments (67).

The salt-tolerant rice variety 'CSR 101' was developed from 'Pusa 44' via marker-assisted selection and gene pyramiding, incorporating the salinity-tolerance QTL (Saltol) and bacterial leaf blight resistance genes (Xa 13 and Xa 21). It was released by Co-operative Vocational Rehabilitation Centre (CVRC) in 2024 in Kerala, Karnataka and Tamil Nadu. The average yield potential in normal and saline and sodic condition is 6.0–6.5 t ha^{-1} and 4.0 t ha^{-1} respectively. The CSR 104 is an early maturing salinity-tolerant rice variety bred by using conventional breeding and field selection methods under salinity and sodic condition. It was released by CVRC in 2024 in Uttar Pradesh and Haryana. The yield potential is 7.0–7.5 t ha^{-1} under normal conditions and 4.5 t ha^{-1} under sodic condition (68, 69).

3. Future prospects and research directions

Despite significant advances in soil salinity assessment and management, several scientific and technological challenges remain. Future research should integrate multidisciplinary approaches combining digital agriculture, biotechnology, climate adaptation and sustainable soil management to improve the resilience of agricultural systems under increasing salinity stress.

Precision agriculture technologies and artificial intelligence applications

Advanced technologies, including remote sensing, UAV imagery, in situ sensors and AI, are currently deployed to check the level of salinity of the soil and the well-being of the plants. This technology helps the farmers in using water and fertilisers efficiently. It reduces waste and enhances productivity of the crops grown in saline soils. Prediction models using AI can be helpful in identifying stress caused by salinity and effective decision-making in farming operations.

The integration of IoT-based sensor networks, cloud computing and big data analytics has further strengthened precision salinity management by enabling real-time collection, storage and analysis of large volumes of soil and crop data. Digital soil mapping techniques facilitate high-resolution spatial assessment of soil salinity, supporting site-specific management practices and efficient resource allocation. Furthermore, explainable artificial intelligence (XAI) improves the transparency and interpretability of AI-based prediction models, thereby increasing user confidence and supporting informed decision-making. Emerging autonomous agricultural systems, including robotic platforms and autonomous field machinery, can perform continuous monitoring and precision application of water, fertilisers and soil amendments, thereby enhancing resource-use efficiency and promoting sustainable management of salt-affected soils.

Integrated soil salinity management

Future research should focus on developing integrated management strategies that combine physical, chemical, biological and agronomic interventions to enhance long-term soil productivity and sustainability. Methods like using gypsum, organic manure, bio-fertilisers, drainage systems and the use of tolerant crops have the potential to increase soil health and agricultural productivity. The use of integrated management methods is believed to be sustainable as it rejuvenates soil productivity.

The successful implementation of integrated soil salinity management requires long-term field validation across diverse agroecological regions to evaluate its effectiveness, stability and environmental impacts under varying climatic conditions. Comprehensive economic feasibility analyses and life-cycle assessments are also needed to determine the cost-effectiveness, sustainability and resource-use efficiency of these management practices. In addition, understanding the factors influencing farmer adoption, including technology accessibility, awareness, training and socioeconomic constraints, is crucial for widespread implementation. Furthermore, supportive government policies, financial incentives, extension services and institutional collaboration are essential to facilitate the large-scale adoption of integrated soil salinity management strategies and promote sustainable agricultural production.

Sustainable and climate-resilient solutions to salinity issue

The issue of salinity will become more acute due to the intrusion of seawater, uneven precipitation and poor quality of irrigation water because of climate change. Consequently, developing climate-resilient agricultural frameworks is imperative. Future research must target the generation of stress-tolerant crop cultivars, effective irrigation and land reclamation. Recent advances in genome editing technologies, particularly CRISPR/Cas9, offer significant potential for developing salt-tolerant crop varieties by precisely modifying genes associated with salinity tolerance. Microbiome engineering through the application of PGPR, endophytes and beneficial microbial consortia can further enhance plant resilience and improve soil health under saline conditions. Digital agriculture tools, including AI, IoT-based sensors, UAV imagery, remote sensing and decision-support systems, enable real-time monitoring of soil salinity and support precision

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management practices. In addition, sustainable water management strategies such as precision irrigation, rainwater harvesting, treated wastewater reuse, conjunctive use of surface and groundwater and efficient drainage systems are essential for improving water-use efficiency and mitigating salinity under changing climatic conditions.

4. Conclusion

Soil salinity remains one of the most significant environmental constraints limiting sustainable agriculture, soil health and global food security. Recent advances in salinity assessment technologies, precision agriculture, biotechnology, nanotechnology and the development of salt-tolerant crop varieties have substantially improved the diagnosis and management of salt-affected soils. Integrated approaches using efficient irrigation, soil treatments, phytoremediation, beneficial microorganisms and climate-tolerant crop varieties are effective methods that sustain production in saline environments. The review highlights substantial progress in soil salinity monitoring through remote sensing and artificial intelligence (AI), advances in sustainable reclamation practices and the rapid development of molecular tools for improving crop salinity tolerance. The adoption of integrated salinity management strategies has the potential to improve crop productivity while enhancing long-term soil health and environmental sustainability. Future research needs to emphasise ecological methods, management using AI and stress-tolerant crop cultivation.

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Authors' contributions

TMN wrote the manuscript. PCNM provided guidance in writing the manuscript. PSP, RMJ, TS and SR reviewed 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.

Ethical issues

None

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