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Promising management strategies to improve crop sustainability and to amend soil salinity

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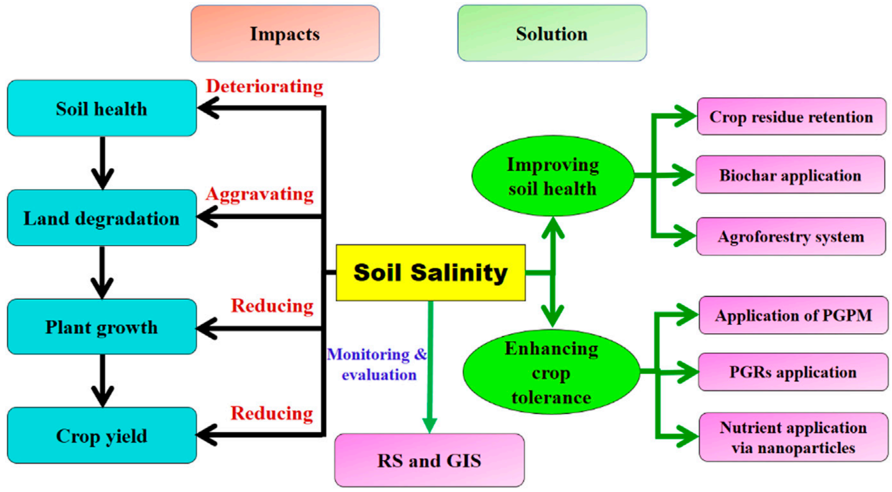
By affecting 10% of the world's total arable land, soil salinity has become a potential threat to feeding the exploding population. As per the current scenario, among 1,125 million hectares of salt-affected land, nearly 76 million hectares are seriously affected due to human-induced salinization. Due to soil salinization, crop productivity is being hampered. In order to enhance productivity, there is an urgent need to shift from traditional methods to advanced 3E (efficient, economic, and environmentally sound) technology for soil salinity reclamation and management to achieve better soil health and sustainable crop production. The detailed mechanism of salt interference with various pathways involved in plant growth and development needs to be understood. This article critically reviews the mechanism of harmful salt interference with nutrient dynamics in soil and various physiological pathways involved in crop growth to apply various soil-oriented (crop residue management, biochar application, and agroforestry system) and plant-oriented [plant growth-promoting microbes (PGPMs), plant growth regulators, and nanotechnology] promising reclamation and rehabilitation approaches to mitigate its hazardous effect on soil salinity. The monitoring and assessment of salt-affected soils through remote sensing (RS) and geographical information systems (GISs) are pivotal in the management and framing of long-term policies to confront alarming threats to crop productivity and sustainability. This study provides an insight into recent developments in soil salinity management and proposes futuristic solutions that could ameliorate soil salinity to attain crop sustainability under adverse environmental conditions.

KEYWORDS

PGPM, nanotechnology, agroforestry, ROS, ethylene, biochar, residue retention



GRAPHICAL ABSTRACT

Introduction

Plants are encountering several environmental adversities caused both by living and non-living factors, with the former known as biotic stress and the latter as abiotic stress. Various stress factors have been found in almost all environments and climatic conditions, but salinity stress seen in plants growing under arid and semi-arid conditions should be given priority. Salinity stress is a form of abiotic stress, which is caused due to salt accumulation in the root zones of plants, making them physiologically flaccid and unfit for production (Munns, 2005; Manchanda and Garg, 2008). Currently, approximately 1.1 × 10^9 ha of land is salt-affected globally, and saline soils are increasing at an alarming rate of 1.5 million hectares annually (Hossain, 2019). The FAO estimated that over 6% of the world's land area and about 20% of irrigated croplands are affected by salinity (Parihar et al., 2015). Nearly 95% of the total degraded land in India (7.5 million hectares) is accounted for by soil salinity/alkalinity, especially found in the states in the north western part (Western Uttar Pradesh, Punjab, Haryana, northern Rajasthan, and Delhi), the central part (Gujarat, central and western Rajasthan, Maharashtra, and Madhya Pradesh), and the north eastern part (West Bengal, central and eastern Uttar Pradesh, Bihar, and eastern Odisha) of India (Choudhary et al., 2018; Kumar and Sharma, 2020). Meanwhile, the human population will reach approximately 9.7 billion in 2050 and, to feed this population, the target is to bring about a 1.7-fold increase in crop yields (Tilman et al., 2011; Yadav, 2020), for which sustainable agriculture with maintained food quality is highly desired.

Containing profuse neutral soluble salts (chlorides and sulfates of sodium, magnesium, and calcium), saline soils inhibit the growth of plants growing in them (Panhwar et al., 2019; Ismayilov et al., 2021). These soils are characterized mainly by a highly elevated water table, the escalated salinity level of underground water, and poor drainage conditions, leading to ceased aeration of the affected soil. Soil salinity affects soil microbial activity and diversity, which in turn disturbs various vital activities in soil, viz., residue decomposition, soil respiration, and nitrogen (N) transformations (Schirawski and Perlin, 2018). The combinations of these problems have rendered large tracts of land unproductive, with direct economic losses. Salinity is developed naturally through primary or human-induced secondary salinity (Shrivastava and Kumar 2015). In a plant system, salt can have an effect in three ways, viz., reducing water potential, which results in osmotic stress (Setia et al., 2013), induced ion imbalance or disturbing ion homeostasis, and ion toxicity due to the excess accumulation of ions in plant cells (Bharti et al., 2016). The majority of physiological processes in plants, including seedling germination, growth, photosynthesis in leaves, and nutrient and water uptake by vascular bundles, are affected by salt stress leading to a decrease in yield (Bartels and Sunkar 2005; Bano and Fatima 2009; Qin et al., 2016), although the type and degree of these effects vary with crops, their growth stages, and their sensitivity to a saline environment. The extent of adverse impacts due to salinity stress is more prominent in dicotyledons ranging from *Arabidopsis thaliana*, which is very sensitive toward salinity, to halophytes such as *Salicornia bigelovii* and *Panicum virgatum* (Pang et al., 2010). Plants have the inherent ability to cope with fluctuations in their ambiance and adversity due to environmental extremities (Simontacchi et al., 2015). The principal defensive mechanisms utilized by plants when exposed to salinity stress can be attributed to ion exclusion by the roots and controlling the uptake and transport of specific ions (Sairam and Tyagi, 2004; Hanin et al., 2016) through carrier proteins, channel proteins, antiporters, and symporters (Gupta and Huang, 2014), as well as tissue tolerance to high ion concentration (Munns and Tester 2008). Plants synthesize and accumulate compatible solutes, such as proline, glycine betaine, sugar (Kerepesi and Galiba, 2000; Ashraf and Foolad, 2007; Hossain et al., 2011), and polyols, that have been reported to maintain cell homeostasis in plants under stress. Furthermore, microbial populations present in soil help boost plants' tolerance mechanisms by activating several internal processes within plants known as plant growth-promoting rhizobacteria (PGPR). Through the activation of the required genes, enzymes, metabolites, and hormones, these beneficial microbes have been reported to have a direct or indirect effect on plant growth and metabolism under various stressful environmental conditions (Bloemberg and Lugtenberg 2001; Yang et al., 2009; Egamberdieva 2012; Panhwar et al., 2014; Naher et al., 2018; Yadav, 2020), such as the solubilization of complex phosphate (Hamdali et al., 2008), siderophore production (Carrillo-Castaneda et al., 2002; Etesami and Beattie, 2017), improving photosynthesis and water use efficiency (Porcel et al., 2012),

TABLE 1 Classification of soil salinity based on the reaction (pH), electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium absorption ratio (SAR) of the affected soil.

Type of soil	Electrical conductivity (dSm^{-1}) of the saturation paste (ECe)	Soil pH	Exchangeable sodium percentage (ESP)	Sodium absorption ratio (SAR)	Physical condition of the soil
Normal	<4.0	6.5–7.5	<15	<13	Good
Saline	>4.0	<8.5	<15	<13	Normal to poor
Sodic	<4.0	>8.5	>15	>13	Very poor
Saline-sodic	>4.0	<8.5	>15	>13	Poor

helping in nitrogen fixation (Bloemberg and Lugtenberg 2001; Etesami, 2018), maintaining ionic homeostasis (Na^+/K^+ ratio) within plant cells (Islam et al., 2016), the alleviation of biotic (Toklikishvili et al., 2010) and abiotic stresses (Dimkpa et al., 2009) through the production of antioxidant enzymes [such as catalase, superoxide dismutase (SOD), and peroxidase (Islam et al., 2016)], volatile substances (Yang et al., 2009; Timmusk et al., 2014), and the regulation of the stress-responsive genes (Gond et al., 2015).

The unwise and random use of fertilizers also results in soil salinity, leading to a decrease in crop productivity (Rütting et al., 2018). Therefore, it is necessary to adopt technologies that could improve crop production, crop residue utilization, and soil fertility. Due to its more significant potential in enhancing soil physico-chemical properties, organic matter could be a game changer in modifying the saline environment into a stable and healthy crop environment (Mahmoud et al., 2009). Improving soil structure, aeration, and aggregation increases the probability of a higher crop yield and healthier soil (Sparks, 1995). Understanding the impacts of salinity both on soil health and plant physiology is necessary to mitigate their adverse effects on crop production. However, there are a few age-old soil salinity remediations, such as leaching or flushing excess salt with quality irrigation water up to the required root zone and regularly scraping the surface salts. In contrast, considering that water scarcity will be a huge problem that will affect crop production worldwide, mostly in arid and semi-arid regions, in the next few decades, sustainable ways to remediate the adverse effects of soil salinity on crop growth and ultimately crop production need to be emphasized. Therefore, this review article is focused on discussing the responses of plants under salinity stress and improving plant performance under a saline environment through various sustainable approaches.

Soil salinity affecting crop sustainability: A call for advanced and efficient remediation measures

Saline soils are categorized as one of the most problematic soils, unsuitable for crop cultivation, due to the accumulation of high levels of adsorbed Na^+ in the soil matrix. Irrigated agriculture usually leads to secondary soil salinization, which affects almost 20% of irrigated lands worldwide as most of the dry regions are devoid of rainfall and depend entirely on irrigation for agricultural practices (Pang et al., 2010; Kumar and Sharma, 2020; Mirlas et al., 2022). Due to insufficient precipitation in arid and semi-arid regions, there is a problem regarding the leaching of salts from surface soil. Their accumulation leads to soil salinization, which is further aggravated due to improper irrigation systems followed for crop production (Shrivastava and Kumar, 2015). There are various measures to categorize saline soils based on the values of the electrical conductivity of saturation extract (ECe), sodium absorption ratio (SAR), or exchangeable sodium percentage (ESP) as saline, sodic, or saline-sodic soil (Table 1). There are many severe effects of salt accumulation on soil health and crop productivity as salts, particularly Na^+ in excess, deteriorate physical soil conditions by clogging the soil pores, causing impermeability, which further leads to crusting and hardpan formation in various layers of the soil matrix (Kumar and Sharma, 2020). Saline soil is defined as one in which the electrical conductivity (EC) of the saturation extract (ECe) in the root zone exceeds 4 dS m^{-1} (approximately 40 mM NaCl) at 25°C and has exchangeable sodium of 15% (Jamil et al., 2011). Values above this level lead to a depreciation in crop production, along with ecological imbalance and deteriorated soil physicochemical properties. Understanding the deleterious effect of soil salinity on various processes in plants represents the first step toward the remediation of salinity-related stress in crops for sustainable crop production.

Soil salinity is hazardous to intrinsic soil permeability and infiltration, especially in saline soil (ECe >4.0 dS m^{-1}). Studies have revealed that excessive salt deposition in the plant rhizosphere makes water entry to the plant system difficult due to high osmotic pressure, which further reduces the soil water potential in the context of crop uptake (Singh et al., 2011; Kumar et al., 2014). However, when it comes to sodic soil, due to excess sodium ion (Na^+) deposition in the soil matrix, the deflocculation of soil particles leads to disturbance in the soil structure and aggregate stability. As a result, a reduced macroporosity is responsible for infiltration, and drainage further aggravates the unavailability of water and nutrients for stress-affected plants (Singh et al., 2016; Mishra et al., 2018a). Salinity, when it persists, gradually reduces the water influx into the vascular bundles present in plant's roots, making the cells flaccid, and the plant gradually suffers from physiological drought. Tang et al. (2020) revealed the signaling mechanism for stomatal closure due to osmotic stress by highlighting cellular Ca^{2+} signaling, which plays a vital role in signal transduction in a plant cell. Here, Ca^{2+} signaling is responsible for activating the CBL1/9-CIPK 23 pathway, which causes stomatal closure in response to salinity stress. Calcineurin B-like proteins (CBLs) are a specific group of Ca^{2+} sensors that decode all Ca^{2+} signals by activating CBL-interacting protein kinases (CIPKs) (DeFalco et al., 2009; Luan, 2009). In the present context, the CBL-CIPK pathway responsible for stomatal closure under abiotic stress has been focused on (CBL1/9-CIPK 23). In response to ionic stress due to the accumulation of Na^+ dominating all other cells in the apoplast and outside the cell membrane, there is the production of hydrogen peroxide (H_2O_2), which is a reactive oxygen species produced in response to salt stress from singlet oxygen ($O_2^{\cdot-}$) (Zhu, 2016). The reactive oxygen species (ROS) molecules enter the plasma membrane

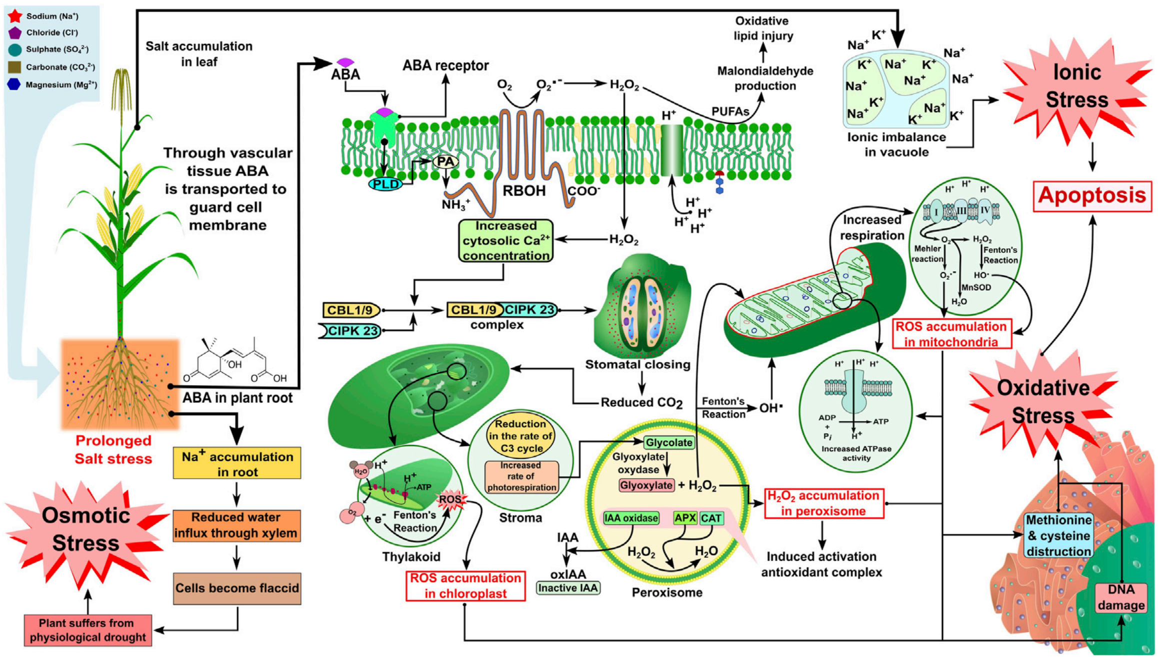


FIGURE 1
Increased salt concentration in soil results in the elevated production of ABA in plant roots, which enters the cell through the ABA receptor and activates the RBOH receptor *via* PLD and PA at the N-terminal of the RBOH receptor. The RBOH receptor stimulates H_2O production from O2 and $O_2^{\cdot-}$, which leads to oxidative injury *via* malondialdehyde (MDA) production and supports the increased concentration of cytosolic calcium ion production. Increased cytosolic calcium ion production further initiates stomatal closing *via* the induction of CBL1/9-CIPK23 complex formation. Stomatal closing contributes toward reduced CO_2 formation in the chloroplast, resulting in an increased Fenton's reaction in thylakoid (leading to ROS accumulation) and a reduced rate of the C3 cycle, as well as an increased rate of photorespiration in the stroma, which accelerates H_2O_2 accumulation in peroxisome affecting the mitochondria (increased Mehler's reaction and Fenton's reaction leading to ROS accumulation and increased ATPase activity), endoplasmic reticulum (methionine and cytosine destruction), and nucleus (DNA damage). The effect on sub-cellular organelles may finally lead to apoptosis *via* oxidative stress. Increased salt concentration may further give rise to an ionic imbalance in the vacuole, leading to apoptosis *via* ionic stress. Increased sodium ion accumulation in the root may also contribute to osmotic stress. ABA, abscisic acid; RBOH, respiratory burst oxidase homolog; PLD, phospholipase D; PA, phosphatidic acid; CBL, calcineurin B-like protein; CIPK, CBL-interacting protein kinase. The concept of the figure was inspired by Mao et al. (2016) and Zhang et al. (2009). The figure template was inspired by Berru (2007), LadyofHats (2013), Rifqi (2017), Fvasconcellos (2007), Manske (2009), Smartse (2010), and Zifan (2016).

and activate Ca^{2+} molecules in response to stress and, again, this signals the CBL-CIPK pathway to close the stomata by losing water molecules (Tang et al., 2020). Stomatal closure leads to stopping the entry of carbon dioxide (CO_2), which has an impact on the Calvin cycle (C3 cycle) within the stroma of the chloroplast and leads to an increased rate of photorespiration, which leads to loss of energy from plant cells, and the process continues to peroxisomes and mitochondria. Increased photorespiration during the conversion of glycolate to glyoxylate by the enzyme glyoxylate oxidase leads to a rise in H_2O_2 accumulation in the peroxisomes (Zhu, 2016; Ma et al., 2020). Such an increase may lead to the activation of an antioxidant enzyme complex [alternative oxidase (AOX)], such as ascorbate peroxidase (APX) or catalase (CAT), which breaks down H_2O_2 to produce water (H_2O) molecules, but another enzyme, namely, indole acetic acid oxidase (IAA oxidase), oxidizes indole-3-acetic acid (IAA) to produce inactive molecules in the cytoplasm (oxidized indole acetic acid) (Moller and Sweetlove, 2010; Wu et al., 2020). On the other hand, the H_2O_2 molecules in the peroxisomes are converted at the same time into hydroxyl radicals (OH) by Fenton's reaction and enter different cell organelles, including mitochondria, which are the powerhouse of the cell (Cruz de Carvalho, 2008; Deinlein et al., 2014). Some studies have revealed an increase in ATPase activity due to ROS accumulation in mitochondria, leading to an increase in the electron transport system (Cruz de Carvalho, 2008; Asthir et al., 2020). Due to the fast electron transport system (ETS), sometimes there is a loss of electrons (e^-) from the complex I, III, and IV, and the skipped electron is often accepted by free oxygen (O_2^-) and is either converted to superoxide radicals ($O_2^{\cdot-}$) by Mehler's reaction or to H_2O_2 and OH· by Fenton's reaction, and there is ROS accumulation in mitochondria (Cruz de Carvalho, 2008; Asthir et al., 2020). The ROS radicals degrade the membranes of the vital cell organelles (chloroplasts and mitochondria), cause damage to deoxyribonucleic acid (DNA) inside the nucleus, and often destructure the essential amino acids (methionine and thiol group of cysteines) present in the rough endoplasmic reticulum (RER) (Van Aken and Van Breusegem, 2015; Zhao et al., 2020). This might be due to their accumulation in the organelles, hence imposing severe stress on plant cells known as oxidative stress. Malondialdehyde (MDA) production is often considered the measure of oxidative stress imposed on plant cells, which is produced due to the oxidation of polyunsaturated fatty acids (PUFAs) present in cell lipid bilayers of the cell membrane during the entry of H_2O_2 inside the cell, causing lipid membrane peroxidation (Marino et al., 2012). As there is an accumulation of Na^+ inside the cell by suppressing other essential ions (K^+ and Ca^{2+}), the vacuole takes the

TABLE 2 Effect of salinity on various physiological and morphological traits affecting crop yield.

S.L. No.	Morphological and physiological traits	Mode of experiment	Crop	Effect of salinity on the trait	Reference
1	Seed germination	Petri plates	*Lasiurus scindicus*	Germination of the seedlings was wholly inhibited at a NaCl concentration of 200 mM	Malik et al. (2022)
2	Photosynthetic activity	Petri plates	*Lasiurus scindicus*	Chlorophyll content was reduced by 90% with 150 mM NaCl solution and was nearly negligible with a NaCl concentration of 200 mM	Malik et al. (2022)
3	Plant growth	Pot culture	*Latuca sativa*	After 21 days of salt solution application, the root length, shoot length, and number of leaves reduced significantly due to the application of 500 mM, 100 mM, and 200 mM NaCl solution	Ahmed et al. (2019)
4	Nutrient uptake	Laboratory study	Genotypes of rice (Cheongcheong, Nagdong, and IR 28)	Significant reduction in critical ion concentrations, i.e., K^+, Ca^{2+}, Zn^{2+}, and $Mg^{2+,}$ with 150 mM NaCl solution application compared to the application of $MgCl_2$ and $CaCl_2$ of similar concentration	Farooq et al. (2022)
5	Crop yield	Field study	*Oryza sativa*	The crop yield was reduced by 50% with an electrical conductivity of 6 days Sm^{-1} compared to 0 days Sm^{-1}	Khan et al. (2022)

excessive Na^+ inside through tonoplast *via* membrane compartmentalization, which develops ionic stress in the plant cell (Tang et al., 2020; Zhao et al., 2020). As discussed previously, a prolonged saline environment can cause protein degradation, membrane lipid peroxidation, cell organelle degradation in plant cells, and physiological drought in plants due to osmotic, ionic, and oxidative stress alone or in combination (Figure 1). A larger part of physiological cycles in plants, including seedling germination, development, photosynthesis in leaves, and supplement and water take-up by vascular groups, is impacted by salt pressure leading to a decline in yield (Qin et al., 2016), and the level of these impacts shifts with crops, their development stages, and their aversion to a saline climate. The effect of excess salt concentration in soil solution on various physiological and morphological traits, which ultimately hampers crop yield and productivity, is summarized in Table 2.

Understanding the effect of excess salt on the plant environment, plants, and plant cells can lead to the development of technologies to mitigate the negative effects of salinity stress on crop growth and physiology.

Advanced approaches toward salinity management

Due to poor irrigation practices and ecologically harmful cropping practices, soil salinity is expected to affect more than 50% of arable land by 2050 (Srivastava and Saxena, 2004). Crop production in saline soil declines due to prolonged salt interference with the plant–soil environment, or productivity sometimes ultimately declines due to extreme salinity. Due to the decrease in production, salinity directly impacts our food security. Therefore, proper and efficient methods for the identification and mapping of saline areas are unavoidable as a precautionary measure and a step toward salinity remediation. Due to the ever-growing population and the limited arable land for cultivation, it will likely not be possible to leave the salt-affected soil devoid of crop production, which requires various advances and innovations in salinity remediation for a sustainable crop production system.

Advances in soil health-oriented approaches

Efficient *in situ* crop residue management: Solution to soil salinization due to residue burning

Crop production nowadays is becoming more intensive, thereby significantly reducing the interval between two crops to manage the residue of the previous crop (Hou et al., 2019). There are different ways of handling crop residues, but farmers are more likely to utilize *in situ* management. Therefore, it is necessary to take into account the proper management of *in situ* residues that sustain soil health and air pollution (Perkins-Kirkpatrick et al., 2017). Over time, adopting crop residue burning as the simplest and most economical way to treat residues has been observed (Ravindra et al., 2019). However, this process has many adverse effects, and soil salinization is known to be one of them. Organic amendment improves plant growth and yield by modifying ionic homeostasis, photosynthetic apparatus, and antioxidant machineries, and by reducing oxidative damages (Hoque et al., 2022). However, the beneficial regulatory role of organic amendments in plants and their stress mitigation mechanisms has received insufficient attention. The emphasis in this section is, therefore, on addressing the adverse effects of residue burning on soil salinization, along with the follow-up action required for an eco-friendly approach to residue management.

Crop residue burning: Aggravating soil salinization

Among the various options for managing crop residues, crop residue burning is a prevalent economical method practiced by most farmers, leading to secondary salinity. Burning on the soil surface interferes with its nutrient cycling and physical, chemical, and biological properties (Certini, 2005). The impact of residue burning is expressed more on the top layer of soil having leaf litter as organic matter and although the availability of some nutrients (K, Ca, and Mg) being enhanced due to its combustion, while several major nutrients become volatilized (N, P, and S). The cation exchange capacity (CEC), aggregate stability, aeration, infiltration, and microbial diversity of soil are affected due to the loss of its organic matter (Bhuvaneshwari et al., 2019). Compared to natural decomposition in the soil environment, residue burning on the surface of soil often leads to the rapid mineralization and volatilization of many essential nutrients (Bhuvaneshwari et al., 2019). An increased soil temperature (34–42°C) resulting from crop stubble burning results in a significant loss of an essential nutrient from the topsoil, namely, nitrogen. Residue burning in a long-term manner has resulted in a reduction of total nitrogen in the topsoil layer (0–15 cm) (Gupta et al., 2003). In a laboratory experiment, a temperature of 250°C lasting 15 min was enough to reduce OM (Jain et al., 2014; Thomaz and Fachin, 2014). Furthermore, the burning of crop residues also influences the acidity of soil as it increases the soil's electrical conductivity (EC) and pH (Huang et al., 2012). Generally, due to the presence of soluble salts, soil salinity hinders water extraction by plant roots due to elevated osmotic pressure on the former, which leads to physiological drought. An increase in soil CEC has been reported, along with an elevated level of other nutrients on residue-treated soils, compared to control groups (Ogbodo, 2011). Thus, it can be concluded that crop residue burning may lead to an increase in soil salinity. The long-term continuous use of this practice can result in a considerable reduction in soil organic C and N. It may lead to detrimental effects on some soil properties and a loss of productivity.

Efficient *in situ* crop residue management

Crop residue recycling improves soil physical (e.g., structure, infiltration rate, plant available water capacity, and soil strength), chemical (e.g., nutrient cycling, cation exchange capacity, and soil reaction), and biological (e.g., SOC sequestration, microbial biomass C, and activity and species diversity of soil biota) quality (Singh et al., 2010; Singh, 2018; Goswami et al., 2020). Long-term residue management also seems promising in reducing soil salinity (Mishra et al., 2018b). Therefore, strategic research on mixed residue recycling needs to be conducted in salt-affected soils to precisely capture the evidence and generate recommendations for management.

Biochar: Ameliorating adverse soil salinity

As a finely grained and highly porous soil amendment, biochar is often distinguished from other charcoal-based soil amendments (Ali et al., 2017). Biochar has been found to be produced under specific heat treatment for the optimization of its specific characteristics, such as a high specific surface area (SSA) and tenacity in soils, circumventing its biological decay (Ali et al., 2017). Its ability to adsorb and retain soil moisture and essential nutrients is mainly based on the porous nature of the amendment (Warnock et al., 2007; Zhang et al., 2014). Due to the presence of surface functional groups (acidic, i.e., carboxylic, phenolic, and lactones; basic-ketones, pyrones, and chromes) produced during pyrolysis (Roy et al., 2022), biochar retains an essential property of adsorption, and this property makes it a suitable and economical option in soil salinity amelioration through the removal and sorption of harmful organic compounds (Ali et al., 2017). The application of biochar in saline soil amelioration, in many ways, is discussed further in this section.

Regulating abscisic acid and stomatal conductance

Increased stomatal conductance and reduced abscisic acid (ABA) are often correlated with biochar-mediated plant growth enhancement under salt stress. Many recent studies have concluded that biochar application is the reason behind improved stomatal conductance in crops (viz., tomato and wheat) (Akhtar et al., 2015b). Studies have reported decreased ABA levels with the application of biochar (Akhtar 2015a), but this is not applicable to all soil types. Many researchers have witnessed a decrease in ABA content due to the synergistic effect of biochar and PGPR under salinity stress (Akhtar, 2015b; Hafez et al., 2019), hence supporting plant growth and development under salinity stress.

Improving ionic balance in the soil environment: Reduction in Na ion toxicity in plants

By interfering with the ionic balance, excess salt causes toxicity in plants. In particular, sodium has been seen to lead to the deterioration of soil physical properties, such as poor soil structure, reduced hydraulic conductivity, and surface permeability, which have been found to have a direct or indirect effect on soil erosion (Sun et al., 2020). It has been reported that sodium ion toxicity negatively impacts soil aggregate stability due to replacement of calcium ions from cation exchange sites (Lashari et al., 2015; Sun et al., 2020). Biochar may represent a cost-effective solution to soil salinity mitigation in agricultural as well as contaminated soils due to its salt sorption capacity, thereby enhancing the CEC of soil when applied with proper doses and combinations (Liang et al., 2010; Kim et al., 2016). Biochar has also been seen to ameliorate salinity stress by reducing Na^+ uptake in plants (Thomas et al., 2013; Lashari et al., 2015).

Effect on the properties of saline soil

Biochar application can act as an effective ameliorant against hazardous abiotic stress, such as salinity stress, by nourishing overall soil properties directly related to Na removal, as mentioned in Section 5.2 (Sun et al., 2016). According to reports, biochar application in its various forms (composted biochars or pyroligneous solutions) can affect the enzymatic activities of salt-affected soils, which also depends on the rate and time of application of the biochar, along with the group of enzymes under study (Rizwan et al., 2016a; Guanming et al., 2017; Luo et al., 2017). When applied with organic matter, biochar shows the significant enhancement of soil organic matter, as well as CEC, and reduces the exchangeable Na and pH of saline soils (Bhaduri et al., 2016; Rizwan et al., 2016b; Ali et al., 2017). Biochar and fulvic acid have been found to improve the overall soil physical and chemical properties, which further adds to the multiple benefits of salt reduction, nutrient supply, water retention, and crop growth (Sun et al., 2020). Biochar, used alone or in various combinations, has been found to enhance the overall physicochemical and biological properties of soil, as summarized in Table 3.

Enhancement of mineral nutrient uptake due to biochar application

Crop production in many parts of the world has declined as a result of soil salinization due to the negative impacts of excessive salts on the water-absorbing capacity of plant roots, which is primarily due to very high concentrations of ions and total dissolved solids (TSSs) in the soil solution (Lashari et al., 2015; Xu et al., 2016). Additionally, salinity causes several nutritional disorders and yield losses by limiting essential nutrient uptake by crop plants (Grattan and Grieve, 1998; Sun et al., 2020). Due to its mineral and water sorption capacity, biochar has been considered an effective amendment in enhancing crop tolerance to salt toxicity (Lashari et al., 2015; Sun et al., 2020). It has been reported that biochar application improves available soil phosphorus in less fertile soils (Subedi et al., 2016). According to Sun et al. (2020), biochar and fulvic acid can release nutrients to the soil for plant utilization under salinity stress. Biochar application has been considered a potential tool for plant nutrient availability, even under salt stress (Table 3). According to reports, the application of biochar has been seen to raise soil pH to some extent, which could hinder crop

TABLE 3 Role of biochar in improving crop tolerance to salinity stress when applied alone or in combinations.

S.L. No	Biochar treatment	Crop	Effect of biochar treatment on salt stress	Reference
1	Biochar as top dressing	*Abuliton theophrasti* and *Prunella vulgaris*	Completely alleviated salt-induced mortality in both the plants and substantially increased the biomass of *P. vulgaris* by 50% as compared to untreated controls	Thomas et al. (2013)
2	Biochar	Potato	Increased shoot and root traits and reduced Na^+/K^+ in xylem and ABA concentration in the leaf	Akhtar et al. (2015a)
3	Biochar with plant growth-promoting endobacteria (*Burkholderia phytofirmans* PsJN and *Enterobacter* sp. FD17)	Maize	Decreased Na^+ uptake and improved the nutrient status of the plants	Akhtar et al. (2015b)
4	Biochar poultry manure compost (BPC) with pyroligneous solution (PS)	Maize crop	Significant increase of carbon and nitrogen both in bulk and rhizosperic soil due to the application of the amendments	Lu et al. (2015)
5	Biochar and arbuscular myccorhiza (AM)	Lettuce	Improved P and Mn uptake in lettuce by combined application	Hammer et al. (2015)

TABLE 4 Ameliorative effect of plantation trees (>10 years) on salinity-affected soils in India.

Sl. No.	Name	pH	EC	Drought resistance and rainfall	N- fixing	Reference
1	*Prosopis juliflora*	>9.8	>35	High (150–750)	Yes	Singh et al. (2011); Banyal et al. (2017); Singh (2018)
2	*Acacia nilotica*	>9.8	15–25	High (200–1500)	Yes	Singh et al. (2011); Dagar (2014)
3	*Tamarix articulata*	>9.8	25–35	High (100–700)	No	Hasan and Alam (2008); Banyal et al. (2017)
4	*Casuarina equisetifolia*	9.1–9.8	15–25	Moderate (700–2000)	Yes	Singh et al. (2011); Banyal et al. (2017)
5	*Salvadora persica*	9.1–9.8	>35	High (300–600)	No	Banyal et al. (2017)
6	*Terminalia arjuna*	>9.8	10–15	Moderate (400–1500)	No	Singh et al. (2011); Singh (2018)
7	*Eucalyptus tereticornis*	9.1–9.8	10–15	Moderate (400–1500)	No	Singh et al. (2011); Singh (2018)
8	*Parkinsonia aculeata*	9.1–9.8	25–35	High (200–1000)	No	Dagar (2014); Banyal et al. (2017)
9	*Albizzia lebbeck*	9.1–9.8	15–25	Moderate (400–1000)	Yes	Dagar (2014); Banyal et al. (2017); Singh (2018)
10	*Pongamia pinnata*	9.1–9.8	15–25	Moderate (500–2500)	Yes	Singh et al. (2011); Banyal et al. (2017)
11	*Zizyphus mauritiana*	9.5	10–15	High (200–1000)	No	
12	*Tamarindus indica*	9.1–9.8	10–15	High (100–700)	No	Banyal et al. (2017)
13	*Azadirachta indica*	8.2–9.0	10–15	Moderate (200–1200)	No	Singh et al. (2011); Banyal et al. (2017)
14	*Acacia leucocephala*	8.2–9.0	10–15	High (400–1500)	Yes	Dagar (2014)

growth in alkaline as well as calcareous soils (Zhang et al., 2014). Therefore, complete laboratory evaluation of the biochar amendment and the targeted soil should be performed before its application to crop fields.

Plantation forestry, social forestry, and agroforestry for soil salinity management

Physical methods, such as surface and subsurface drainage and the application of chemical amendments, are viable remedies to reclaim these soils, but they are either costly or sometimes comparatively inefficient. The agroforestry system has been identified as one of the most suitable environment-friendly soil remediation strategies against land degradation problems as the former has been found to be comprised of multiple components, such as plantation, crops, and horticultural crops, as well as animal husbandry and aquaculture (Dagar and Minhas, 2016). The main environmental benefits of agroforestry systems are carbon sequestration and water quality enhancement, which often lead to an improved soil across all environments (Dagar, 2014; Kumar et al., 2015). Many successful experiments have been performed in India on ameliorating salt-affected soils through the practice of tree plantations and agroforestry on those soils (Kumar et al., 2020). A 20-year-old tree plantation (*Prosopis julifera*, *Acacia nilotica*, *Terminalia arjuna*, *Albizzia lebbeck*, and *Eucalyptus tereticornis*) in alkali soil was found to be effective in the amelioration of salt in a salt-affected soil (Dagar, 2014). Significant decreases in soil pH and EC levels have been reported under different plantations of varying ages. It has been reported that silvopastoral and tree plantation systems have improved soil organic carbon and, thereby, microbial activity when adopted in sodic soils (Dagar, 2014; Arya and Lohara, 2016; Gupta and Dagar, 2016). Reported a considerable carbon sequestration potential of 157.26 Mg C ha^{-1} for the plantation of *Grevillea robusta* raised on sodic soil over 25 years. A decrease of 3.39 dS/m in the EC level and a 23% increase in SOC have reported an 8-year-old intercropped *Eucalyptus* plantation at 3 m × 3 m spacing (Kumar et al., 2019). Basavaraja et al. (2010) estimated a decrease of 1.3 in soil pH in a 10-year-old *Acacia nilotica* plantation. A decrease in the range of 0.90–2.45 in pH and 1.05–1.41 dS m^{-1} in the soil EC level for agroforestry systems of *Prosopis juliflora, Terminalia arjuna*, and *Tectona grandis* with rice-berseem cropping pattern being observed by Kaur et al. (2020a) and Kaur et al. (2020b). These studies demonstrate that tree plantations and agroforestry systems can efficiently be applied as remediation and restoration strategies for degraded and marginal lands (Table 4).

Advances in crop growth-oriented approaches

Role of microbes in the regeneration of saline agro-ecosystems

Excess salt interferes with plant biology, viz., photosynthesis, protein synthesis, and lipid metabolism (Kumar and Verma, 2018). Because microorganisms communicate with plants and support the living environment, they are considered to constitute an essential part of plant defense to deter numerous stresses. Microorganisms can live in various conditions and thus have an immense capacity to minimize stress through their metabolism, such as salinity (Meena et al., 2017; Kerry et al., 2018; Das et al., 2020a). As an important indicator of soil health, soil microbial biomass (SMBC) plays a major role in recycling organic matter and enhancing soil fertility (Xu et al., 2020). Salinity has adverse effects on microbial structure, composition, and functions. The application of microorganisms as bio-fertilizer under saline soil promotes agriculture yield and soil status (Daliakopoulos et al., 2016; Tiwari et al., 2016). Owing to their versatility, ubiquity, and unmatchable capacity, microbes offer an innovative and feasible option in saline agricultural technology (Singh et al., 2011; Singh et al., 2016). Such microbes are often termed plant growth-promoting microbes (PGPMs). Various microbes have been reported for their tremendous properties under saline conditions.

The saline stress environment exceeds plant hormone ethylene levels, known as stress ethylene (Kumar A. et al., 2020). Stress ethylene is generally detrimental to plant growth and is frequently involved in introducing chlorosis, senescence, and abscission. As an instant precursor of ethylene biosynthesis, aminocyclopropane-1-carboxylate (ACC) is found to be hydrolyzed to microbes utilizing α-ketobutyrate and ammonium ions (NH_4^+) due to the activity of an enzyme present in microbes known as 1-aminocyclopropane-1-carboxylate deaminase (ACCD) (Glick, 2014; Ansari et al., 2019). Various ACCD-producing PGPMs have been reported in recent years for their beneficial effects and minimizing stress ethylene concentration under different abiotic and biotic stress environments by colonizing plant roots under saline environments (Vimal et al., 2017; Ansari et al., 2019). Plant–microbe interactions under saline stress exert beneficial effects both on the plants and microbes involved as microorganisms containing ACC deaminase activity minimize ethylene concentration due to ACCD activity and the plants provide a source of nutrition to the microbes *via* the intermediates produced due the enzymatic activity (α-ketobutyrate and NH_4^+) (Figure 2). Many PGPMs have been reported to produce exo-polysaccharides (EPSs), which form a biofilm and protect plants from hydric stress, enhance water retention potential, and maintain the mass of carbon sources (Upadhyay et al., 2011; Mukherjee et al., 2019). The microbial EPSs stabilize soil aggregates by binding Na^+ and Cl^- ions and hence improve nutrient and water transmission movement across plant roots (Figure 2). The microbial production of IAA induces the root architecture to enhance nutrient uptake and improves plant health under salt stress (Mukherjee et al., 2019; Bhat et al., 2020). Some microbes possess antioxidant enzyme complexes (AOX), such as CAT, monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione S-transferases (GST), and APX, resulting in the hydrolysis of ROS, such as catalase and peroxidases, thus reducing salinity toxicity (Figure 2). Microbes enhance osmolyte accumulation, such as proline and sugars, in plants and increase the K^+ level and maintain the Na^+/K^+ ratio (Ruppel et al., 2013; Bhat et al., 2020). Microbe-mediated saline stress management has been reported in many crops in various geographical locations (Table 5). These microbes show potential biological solutions to promote plant architecture under saline stresses. The commercial application of microbial formulations in saline agro-ecosystems is a latent approach for saline agriculture (Mukherjee et al., 2019; Kumar A. et al., 2020).

Role of plant growth regulators in mitigating salinity stress

Plant hormones are organic substances produced by plants that stimulate a physiological response. When synthesized chemically, they are called plant growth regulators (PGRs). Ethylene, auxin (IAA), abscisic acid (ABA), jasmonic acid (JA), and salicylic acid (SA) are just a few of these. Survival under biotic and abiotic stress conditions involves sophisticated crosstalk between phytohormones (Koo et al., 2020). Cell ion homeostasis disturbed due to salt stress increases cytosolic the free Ca^{2+} ion concentration. ABA signals a secondary messenger, Ca^{2+}, to be released from membrane channels or vacuoles into the cytoplasm, which helps cope with high Na^+ concentrations (Quan et al., 2007). ROS, essential signaling molecules, together with ABA and Ca^{2+}, exhibit complex signaling crosstalk to control plant growth responses to salt stress. Indole acetic acid improves the number of photosynthetic pigments that promote carbohydrate formation and thus increases stem diameter, an essential parameter in the case of fodder crops (Waheed et al., 2014). Salt stress induces physiological stress and reduces water absorption by roots, the partial closure of stomata, restricted photosynthesis, and the accumulation of ROS (Wang et al., 2016). It has been suggested that, to enhance plant tolerance to soil salinity, antioxidants such as ascorbic acid and glutathione promote the homeostasis of Na^+/K^+ and ROS (Tao et al., 2015). Sulfur is an integral part of proteins and hormones necessary for oilseeds and the active metabolism of nitrogen, which is improved by salicylic acid spray (Rajabi Dehnavi et al., 2019).

According to the activation of non-selective cation channels (NSCCs) through ROS, which causes K^+ leakage, can be controlled by SA application to plants. It has been reported that silicon (Si) application can directly or indirectly mitigate oxidative stress in plant cells *via* the regulation of the antioxidant defense system and the metabolism of polyamines (Liang et al., 2010; Zhu et al., 2019). The addition of Si in chickpeas has resulted in the reduced absorption and translocation of Na^+ due to enhanced H^+-ATPase activities in the vacuolar membrane of the plant cells. Studies over the decades have

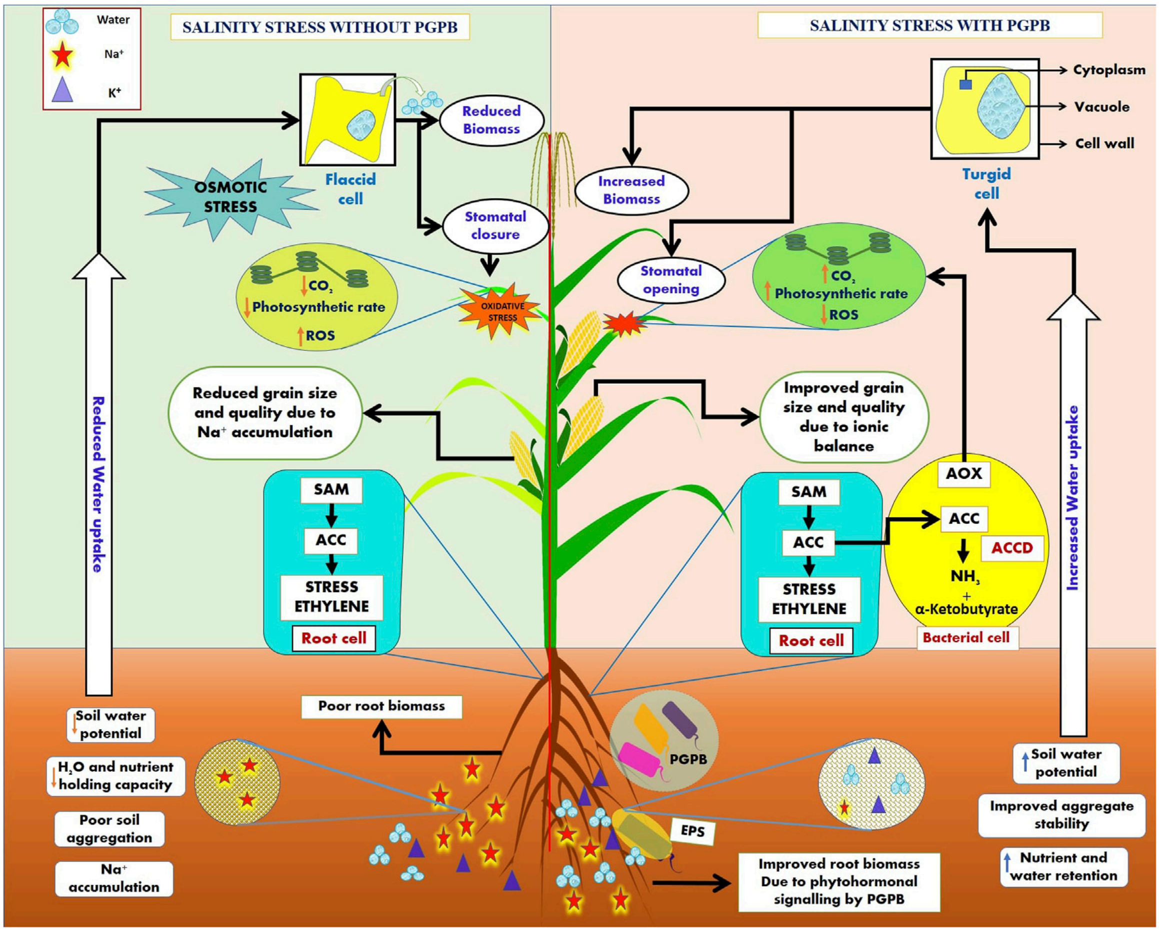


FIGURE 2
Plant growth-promoting bacteria (PGPB) mediate the salinity stress mitigation mechanism in plants *via* exopolysaccharide (EPS) secretion and the production of an antioxidant enzyme complex (AOX) to reduce reactive oxygen species (ROS) in cell organelles and ACC deaminase (ACCD), which reduces the stress ethylene in salt-stressed cells. The concept of the figure was inspired by Egamberdieva et al. (2019), Narsing Rao et al. (2019), and Soni et al. (2018).

shown a beneficial effect of several natural and synthetic PGRs on plant growth and regulation; some of these are listed in Supplementary Table S1.

Nanotechnology in salinity management

The uncontrolled and excess use of agrochemical fertilizers has become the primary threat to soil health, leading to extreme salinity in the soil. Currently, there is a paucity of information on the impact of nano-materials on soil salinity management. Nanoparticles are widely agreed to be a cluster of atoms in the size range of 1–100 nm (Pan and Xing., 2012; Kerry et al., 2017; Kerry et al., 2019). It is also known that nanoparticles have a high surface-to-volume ratio, and their bioavailability could be significantly greater than larger particles (Shalaby et al., 2016). Their large surface area enhances the reactivity and easier delivery of particles to porous soils, making nano-materials significant amendments for soil reclamation (Liu and Lal, 2012). Researchers have used nanoparticles as a nutrient carrier, but there is also a concern that they may be lethal, depending upon the quantity of application and the nature of the nanoparticles. Furthermore, the abundance and diversity may shift in response to foreign nano-materials in the soil. The idea of nanoparticles in the soil can be attributed to nano-fertilizers and is one of the most promising methods to reduce environmental pollution (DeRosa et al., 2010).

Nano-iron oxide treatment in saline soil has also improved the mean weight diameter and infiltration rate (Ghodsi et al., 2011) and has facilitated the formation of soil macroaggregates and microaggregates (Liu and Lal, 2012). A study concluded that the controlled application of nano-materials in the rhizosphere significantly enhances the microbial population; it was observed that, through the application of 100 mg kg^{-1} nano-Fe_2O_3 and nano-ZnO treatments at an elevated CO_2 level, the microbial biomass carbon was highest. In contrast, a sharp decrease was noted at a higher concentration compared to the ambient CO_2 level (Yadav et al., 2014). Mimicking the saline environment by applying NaCl with varying concentrations, various researchers have studied the impact of no fertilizer, typical silica fertilizer, and silica nanoparticles on soil health. According to reports, sodium chloride (NaCl) induces soil salinity and reduces plant growth, but when soil salinity is combined with Si nanoparticles, enhancement in chlorophyll content is observed, along with the fresh and dry weight of the shoots (Kalteh et al., 2014; Tantawy et al., 2015).

TABLE 5 Effect of different microbes on plant health under salinity stress condition.

Sl. No.	Plant	Salt concentration	Crop growth condition	Microorganism	Role of microbe	Reference
1	*Triticum aestivum*	2.0 and 6.0 dSm^{-1}	Field condition	*Bacillus* sp., *Enterobacter* sp., *Microbacterium* sp., *Paenibacillus* sp., *Burkholderia cepacia*	Reduced plant cation uptake, and enhance status	Upadhyay et al. (2011)
		1.0, 3.0, 6.0, 9.0, 12.0, and 15.0 dSm^{-1}	Pot culture	*P. putida*	Enhanced germination percentage, GRI, and improved nutrient profile	Nadeem et al. (2013)
		50 mM, 100 mM, and 150 mM	Field experiment	*Bacillus aryabhattai* EWR29	Enhanced siderophore and IAA production, production of exopolysaccharides (EPS), and promoted SOD and POD activities	Farahat et al. (2020)
		3,000 ppm and 5,000 ppm	Pot experiment	*Bacillus megaterium* NBRC 15308 and *Pseudomonas fluorescens* NBRC 14160	Improved nitrogen fixing and ACC deaminase activity	Fathalla and Abd el-mageed (2020)
		4.0 dSm^{-1}, 8.0 dSm^{-1}, and 16.0 dSm^{-1}	Growth chamber	*Bacillus siamensis, Bacillus methylotrophicus, Bacillus* sp.	Induced ACC deaminase activity	Amna et al., 2019
2	*Hordeum vulgare*	1% NaCl, 9.4 dSm^{-1}, and 6.0–24.0 dSm^{-1}	Pouch assays, greenhouse condition, and field, respectively	*Acinetobacter* spp., *Pseudomonas* sp.	Enhancement in production of ACC deaminase and IAA	Chang et al. (2014)
		36.50 dSm^{-1}	Field experiment	*Bacillus amyloliquifaciens*	Increase in seedling length, gain in plant fresh and dry weight, and relative water contents	Kasim et al. (2016)
3	*Oryza sativa*	40 mM and 80 mM	Pot culture	*Halobacillus dabanensis* SB26	Increased plant height, chlorophyll content, and yield	Rima et al. (2018)
		50 mM, 100 mM, and 150 mM	Field experiment	*Halobacillus dabanensis* GSP34		
		>7.45 dSm^{-1}	Field condition	*Bacillus aryabhattai* and *Klebsiella* sp. PD3	Enhanced resistance to heavy metal toxicity	Sultana et al. (2020)
5	*Zea mays*	>10 dSm^{-1}	Field condition	*Pseudomonas syringae*	Activated ACC deaminase	Nadeem et al. (2007)
		1% NaCl	Pot culture	*Bacillus aquimaris* DY-3	Maintained plant–water relationship, development of pigment system (PS), and promoted antioxidant enzyme activities	Li and Jiang, (2017)
		200 mM and 400 mM NaCl	Pot culture	*Gracilibacillus, Bacillus, Pseudomonas* sp., and *Arthrobacter*	Induced IAA production, ACC deaminase activity, and phosphate solubilization	Aslam and Ali, (2018)
		1 M NaCl	Greenhouse study	*Bacillus* sps	Enhanced plant response through activated defensive enzymes; improved traits such as chlorophyll, proline, and soluble sugar	Misra and Chauhan, (2020)
7	*Glycine max*	200 mM NaCl	Plant growth chamber	*Pseudomonas koreensis* AK-1	Reduced Na^{+}/K^{+} ratio	Kasotia et al. (2015)
		200 mM NaCl	Pot culture	*Arthrobacter woluwensis, Arthrobacter aurescens, Microbacterium oxydans, Bacillus megaterium,* and *Bacillus aryabhattai*	Increased ABA content, chlorophyll contents, and increased SOD activity	Khan et al. (2019)
		100 mM NaCl	Pot culture	*Bacillus subtilis* SRM-3 and *Pseudomonas pseudoalcaligenes* SRM-16	Reduced MDA contents, improved shoot and root growth, RWC, total protein content, and photosynthetic pigments	Yasmin et al. (2020)
8	*Phaseolus mungo*	3.0, 5.0 and 7.0 dSm^{-1}	Field experiment	*Pseudomonas fluorescens*	Improvement in water relation and photosynthetic content	Yasin et al. (2018)
9	*Vigna radiata* (L.)	5.59 dSm^{-1}	Field study	*Rhizobium* sp.	ACC deaminase	Aamir et al. (2013)
		200 mM, 500 mM, and 1000 mM	Pot culture	*Rhizobium pusence*	Nodulation and nodule nitrogen enhancement under salinity stress	Das et al. (2020b)

(Continued on following page)

TABLE 5 (*Continued*) Effect of different microbes on plant health under salinity stress condition.

Sl. No.	Plant	Salt concentration	Crop growth condition	Microorganism	Role of microbe	Reference
10	*Arachis hypogea*	4.5 dSm^{-1}	Field trials	*Pseudomonas fluorescens*	Enhanced activity of ACC deaminase	Saravanakumar and Samiyappan, (2007)
11	*Cajanus cajan* (L.)	4.0, 6.0, and 8.0 dSm^{-1}	Greenhouse (pot experiment)	*Glomus mosseae*	Enhanced plant dry mass and nitrogen fixing through improved growth of root nodules	Garg and Chandel, (2011)
12	*Pisum sativum*	200 mM	Field study	*Arthrobacter protophormiae* and *Glomus mosseae*	Reduction in lipid peroxidation and increase in pigment status	Barnawal et al. (2014)
13	*Avena sativa*	1% NaCl, 9.4 dSm^{-1}, and 6.0–24.0 dSm^{-1}	Pouch assays, greenhouse condition, and field, respectively	*Acinetobacter* spp.	Activated ACC deaminase	Chang et al. (2014)
14	*Phaseolus vulgaris*	8.0 dS m^{-1}	Field study	*Rhizobium* sp.	Increased nutrient content and dry weight	Yanni et al. (2016)
		25 mM	Pot culture	*Paenibacillus* sp.	ACC deaminase activity	Gupta and Pandey, (2019)
15	*Gossypium hirsutum*	100 mM NaCl and Mg_2SO_4 solution	Pot culture	*Pseudomonas putida* R4 and *P. chlororaphis* R5	Improved seedling traits	Egamberdieva et al. (2015)
		150 mmol L^{-1} NaCl	Laboratory experiment	*Pseudomonas oryzihabitans*	Promoted seed germination	Irizarry and White, (2017)
		10.51 dS m^{-1}	Pot culture	*Bacillus* sp.	Improved germination traits, chlorophyll contents, and proline content	Saleem et al. (2021)
17	*Capsicum annuum*	40, 80, and 120 mM NaCl	Black containers filled with coconut coir fiber	*Azospirillum brasilense*	Increased photosynthetic rate	del Amor and Cuadra-Crespo (2012)
18	*Lycopersicum esculentum*	120 mM and 207 mM NaCl	Pot culture	*Achromobacter piechaudii*	Reduced stress by ethylene in seedlings	Mayak et al. (2004)
		30, 50, and 180 mmol m^{-3} NaCl for irrigation	Field study	*Streptomyces* sp. strain PGPA39	More gain plant total biomass	Barassi et al. (2006)
		1–8% NaCl	Pot culture	*P. stutzeri, P. aeruginosa*	Increased plant biomass	Tank and Saraf, (2010)
		2.59 dSm^{-1}		*Enterobacter* sp. EJ01	ROS scavenging activity	Ilangumaran and Smith, (2017)
		120 mM, 250 mM, and 500 mM NaCl; and 50 mM glycine betaine	Pot condition	*Leclercia adecarboxylata* MO1	Regulation of endogenous secondary metabolites	Kang et al. (2019)
19	*Lactuca sativa*	2 g NaCl/Kg soil and 4 g NaCl/Kg soil	Pot culture	*Azospirillum brasilense*	ACC deaminase and enhanced plant architecture	Kohler et al. (2010)
20	*Helianthus annus*	125 mM	Pot experiment	*Pseudomonas aeruginosa* PF07	EPS production	Tewari and Arora, (2014)
		3.68 µS cm^{-1}	Pot culture	*Planomicrobium chinense* and *Bacillus cereus*	Increased leaf chlorophyll content and reduced leaf MDA content	Khan et al. (2018)
		125 mM	Field condition	*Pseudomonas aeruginosa* $PF23^{EPS+}$	Improved growth parameters, chlorophyll contents, leaf area stem width, and seed yield	Tewari and Arora, (2018)

The availability of micronutrients in saline soil is the most common problem that arises due to abundant calcium salt, which negatively impacts cop production. Higher alkaline pH reduces zinc availability in the soil. In contrast, ZnO application in the form of nanoparticles can solve the problem due to the provision of a more soluble form of Zn with comparatively higher reactivity than bulk with higher calcium incidence (Duhana et al., 2017). Recently, Hussein and Abou-Baker (2018) investigated the influence of nano-zinc fertilizer

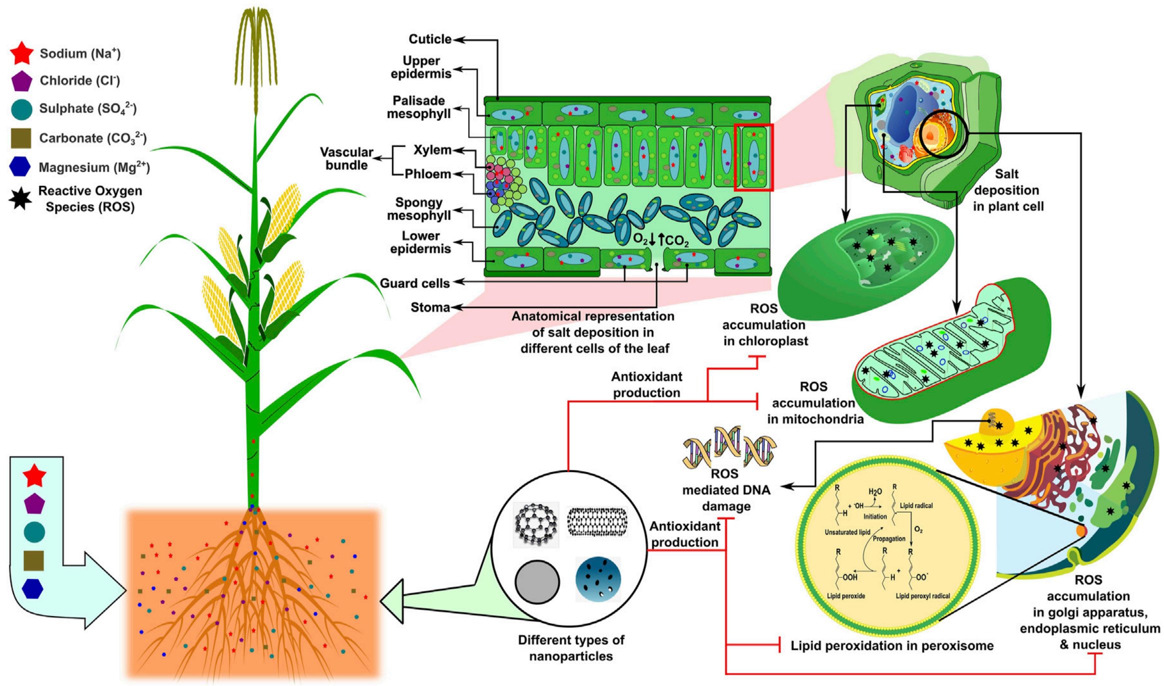


FIGURE 3
Higher salt concentration in plant cells results in a salt deposition in the leaf, leading to reactive oxygen species (ROS) accumulation in the chloroplasts, mitochondria, and nucleus. ROS accumulation in sub-cellular organelles may further lead to DNA damage and lipid peroxidation, which can be neutralized by applying nanotechnology, specifically nano-delivery systems *via* the induction of antioxidant production and/or the direct inhibition of ROS production. The concept of the figure was inspired by Avestan et al. (2019) and Hussein and Abou-Baker (2018). The figure template was inspired by Berru (2007), Forluvoft (2008), LadyofHats (2013), LadyofHats (2006), McKenna (2006), Qef (2009), and Rifqi (2017).

application on the mineral status as well as the growth and yield of *Gossypium barbadense* L. under salinity stress. The results corroborated that the negative impact of adverse salinity on crop production could be mitigated by nano-Zn (Hussein and Abou-Baker, 2018). An experiment by Avestan et al. (2019) showed that the treatment of nano-silicon dioxide could effectively alleviate tolerance to salt stress in *Fragaria ananasa*. Under salinity stress, an acute ionic imbalance or ionic toxicity is observed in the plant rhizosphere, which hinders balanced nutrition in the plant, thereby restricting its growth and yield as described previously. In this section, we describe how nanoparticles can be used as a carrier of many vital nutrients needed for plants that can be carried quickly due to their small molecular size inside the plant cells, thereby maintaining the ionic homeostasis in many of the cell organelles, such as chloroplasts, mitochondria, endoplasmic reticulum, vacuoles, and cytoplasm (Figure 3). Researchers are trying to fill the gaps regarding nano application and interaction with plants owing to the fact that their fate must be conceived on the geosphere (pedosphere)–biosphere–hydrosphere–atmosphere continuum; the time lag of emerging technologies reaching farmers' fields, especially given that many emerging economies are unwilling to spend on innovation; and the lack of foresight due to agricultural education not attracting a sufficient number of brilliant minds from around the world, while personnel from related disciplines may lack the required understanding. Recently, the United States Environmental Protection Agency (USEPA), the Food and Drug Administration (FDA), and the Institute for Food and Agricultural Standards (IFAS) in the United States have developed protocols and procedures for dealing with nano-material production and use, as well as potential threats to people, animals, and the environment. The product concentration, particle size, shape, surface area, crystal structure, dose, exposure time, pre-exposure, and crystal structure effect are the factors used to assess the toxicity of nano-materials. It is necessary to ascertain the tolerable safety limits and toxicity of nanoparticles toward the soil.

Role of remote sensing (RS) and geographical information systems (GISs) in salinity mapping

For mapping wasteland areas, RS and GIS data have been extensively used (Allbed and Kumar, 2013) and have led to the successful reduction of soil salinity through various recovering activities, from site selection to soil monitoring and soil monitoring to groundwater monitoring. The National Remote Sensing Centre (NRSC) has prepared wasteland maps of most of the Indian states based on visual interpretation of IRS P6 LISS-III and LISS-IV geocoded satellite imagery on a 1:50,000 scale since 1985 (Sahu et al., 2016). RS, GISs, modeling, geo-statistics, and advanced electromagnetic induction are the preeminently discussed tools for assessing, mapping, and monitoring soil salinity (Srivastava and Saxena, 2004). Various kinds of spatial and non-spatial data for wasteland management in a particular

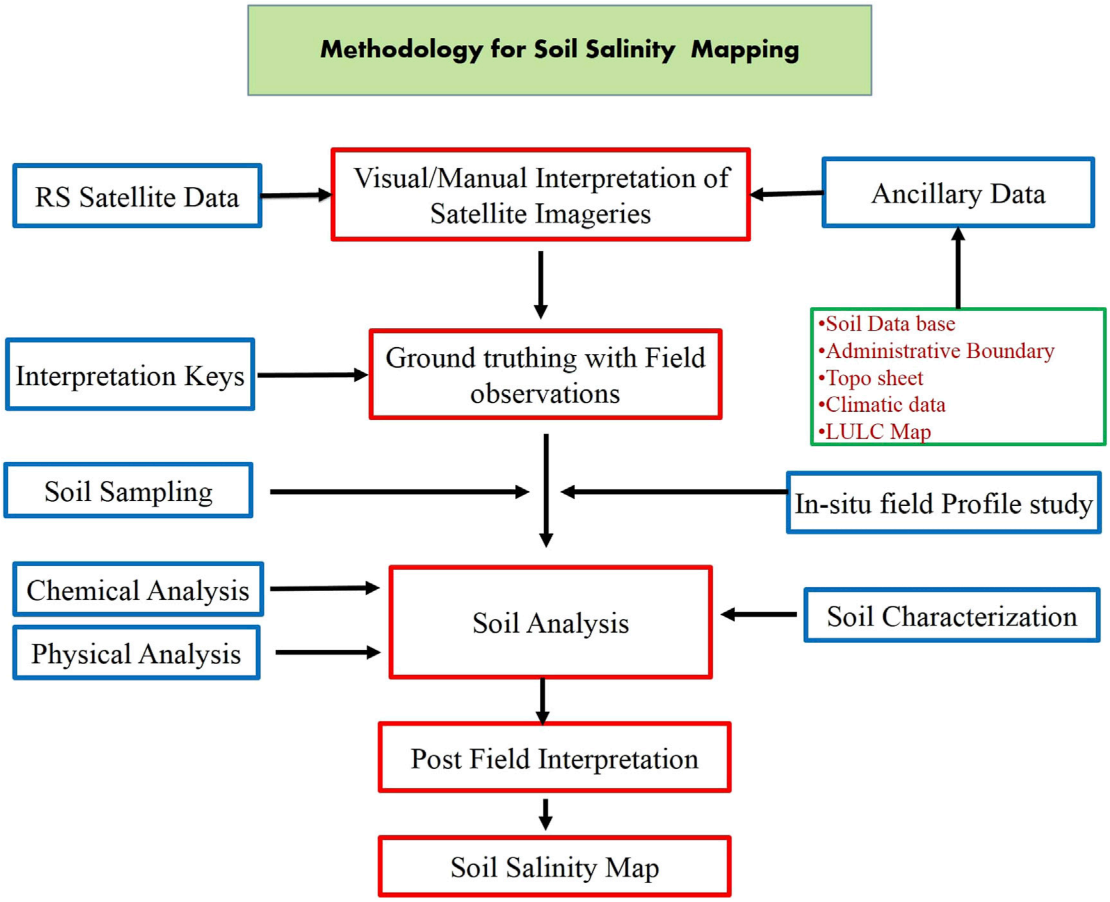


FIGURE 4
Methodology for soil salinity mapping (Abuelgasim and Ammad, 2019; Taghadosi et al., 2019).

district or region can be captured, stored, manipulated, and analyzed *via* RS and GISs. RS technology is time-saving, faster than ground methods, and gives comprehensive coverage facilitating long-term monitoring. Multispectral and hyperspectral sensors have been used for mapping and ascertaining soil salinity (Allbed and Kumar, 2013).

The conceptual basis for RS monitoring has been fabricated upon the spectral characteristics of saline soils. Spectral analysis denotes a detailed examination of the electromagnetic radiation reflected by the target to determine its properties (Harti et al., 2016). The spectral analysis of salt-affected soils serves as a non-destructive, less laborious, and time-saving technique for monitoring the salt-affected soils on a large area's spatial and temporal basis, which may further be used for preparing maps and providing early warnings, as well as for determining the feasibility of any reclamation measures. The spectral analysis of bare soils has revealed that salt-affected soils have higher reflectance in the wavelength range of 0.4–0.9 μm compared to average soils (Castaldi et al., 2016). Salt-affected soils having a surface crust show the highest reflectance, followed by salt-affected soils without a crust, whereas ploughed soil shows the most negligible reflectance (Harti et al., 2016). The reflectance from the saline soil increases with an increase in the severity of the salinity (Kahaer and Tashpolat, 2019). The l-band of the microwave radiation can distinguish between saline and sodic soils at varying moisture levels because the imaginary part of the complex permittivity increases with an increase in electrical conductivity (EC). At the same time, the sodium adsorption ratio (SAR) does not affect either the real or imaginary parts (Sahu et al., 2016). Vegetation indirectly indicates the characteristics of salt-affected soils due to its retarded growth (Masimbye et al., 2012) and increased reflectance in the wavelength ranging from 0.9 to 2.5 μm caused by the increased thickness of the leaves (Sidike et al., 2014). Methods in soil salinity mapping involve ground truthing with field observations from the visual interpretation of satellite imageries collected from RS data (Nguyen et al., 2020). The ground truth observations point to a way forward toward soil sampling and analysis (soil characterization, and physical and chemical analyses) in affected regions by interpreting which soil salinity map is being prepared (Figure 4).

Conclusion

Soil degradation, particularly through salinity, impedes the productivity of croplands and thereby poses challenges in securing livelihoods. A multidimensional approach has shown promising results in reducing soil salinity in different Indian agroecological situations. Strategic and adaptive research on the incorporation of modern technologies, salt-tolerant varieties, biochar, PGPR, and nanoparticles will be critical in amending salt-affected soil and increasing the productivity of degraded land. Because of diversification into other sectors, cultivable land in India is shrinking; the restoration, amelioration, and management of salt-affected soils appear promising for land expansion and production enhancement to ensure food and livelihoods.

Future strategies

Soil quality characteristics are commonly used to assess sustainable land management in agro-ecosystems. Over the last two decades, several land management studies have been conducted in India and elsewhere regarding reducing the salinity and improving the productivity of the land. Unfortunately, there is insufficient data to provide critical remarks on the best working and ecofriendly techniques that should be practiced for salinity remediation in the enhancement of crop production. Plant-associated microorganisms as biofertilizers can promote agriculture yield and soil status under saline soil (Das et al., 2020). These organisms constitute endophytic microbes and symbiotic fungi in the rhizoplane and rhizosphere and they act in many ways, such as initiating the osmotic reaction, growth hormones, and nutritional elements, working as biocontrol agents by inducing specific genes in crops. Biochar and crop residues could be used to ameliorate salinity stress by improving the physical and thereby biological status of the soil and reducing the uptake of Na^+ by plants. At present, nanotechnology is being adapted for specific nutrient availability purposes, and it is also being used for conserving soil fertility and reducing the impacts of salinity from the soil. Many studies have revealed that tree plantations and agroforestry systems could efficiently be applied as remediation and restoration strategies for degraded and marginal lands. Many salt-tolerant species or halophytes with potential agricultural or industrial value can be grown in degraded saline areas as cash crops or commercial crops. Proper land evaluation is considered an essential component for managing any degraded lands, including salt-affected ones, to model the best suitable cropping practices to achieve a sustainable agricultural system. In the field of salinity, research is needed, particularly on land evaluation and opportunities for salinity management in the agro-ecosystem to enhance land productivity. Globally, soil salinity poses a severe menace to food security and threatens millions of small and marginal farmers' livelihoods. Low-cost, need-based, site-specific restoration and amelioration programs should be strategically planned and implemented in order to counter soil salinity. Developmental research on integrating modern technologies, salt-tolerant varieties, biochar, PGPR, and nano-gypsum will be of great significance in reducing salt-affected soil and increasing the productivity of degraded lands. In addition to technological solutions, socio-economic and political considerations are critical in mitigating soil salinization. Farmers need to be provided with various incentives rather than subsidies to undertake corrective salinity measures.

Author contributions

AM: conceptualization, writing and supervision of the manuscript, and critical revision. RD: data collection, interpretation, writing original draft, and graphics. RG: data curation, and graphics and editing. BB: table incorporation and editing. TS: tabular information and editing. SS: review and editing. PA: review and editing. MK: critical review.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.962581/full#supplementary-material

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