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Phytoremediation: An Eco-friendly Approach in Present Scenario for Salt Affected Soil

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INTRODUCTION

Globally, rapid population growth increasing demands and unscientific human activities have accelerated soil deterioration. Both primary (natural) and secondary (anthropogenic) processes contribute to land degradation, resulting in a continuous decline of cultivable land. The annual reduction of cultivable land by about 1–2% poses a serious threat to sustainable agricultural productivity, food security and nutritional requirements of the growing population. Among various forms of soil deterioration, salt-affected soils represent a major global concern. Salt-affected soils are defined as soils containing excessive dissolved salts and/or exchangeable sodium that adversely affect plant growth, development and physiological functions (Qadir et al., 2000). These salts mainly include chlorides, sulfates, carbonates and bicarbonates of calcium, magnesium and sodium. The term salt-affected soils encompasses both saline and sodic soils.

Extent and Distribution of Salt-Affected Soils

Global Scenario

The extent and distribution of salt-affected soils yet have not been precisely studied globally. Current data has shown that the global extent of salt-affected soils is about 1128 Mha, of which approximately 60% are saline, 20% are sodic and 14% are saline-sodic. On a severity basis, the majority of salt-affected soils are slightly affected (65%), followed by moderately (20%), extremely (10%), and highly salt-affected soils (5%). Nearly all over the world salt-affected soils are found which vary in extent and severity. The largest area of salt-affected soils is the Middle East (189 Mha), Australia (169 Mha), North Africa (144 Mha) and the former USSR (126 Mha) (Wicke *et al*. 2011).

Indian Scenario

In India, 6.74 Mha area is salt affected in which sodic soil comprises 3.77 Mha which is 56% of the total salt-affected area followed by 1.71 Mha of saline soils which is 25% of the salt-affected area. A large extent of states like Gujarat, Uttar Pradesh, Maharashtra, Andhra Pradesh, Rajasthan, Tamil Nadu, Haryana, etc. are affected (CSSRI, Karnal, Haryana, 2015).

Occurrence and Sources of Development of Salt-Affected Soils

Salt-affected soils predominantly occur in arid and semi-arid regions due to high evaporation and low rainfall but they are also present in some humid and sub-humid regions where conditions favor salt accumulation. Globally, the increasing use of low-quality and untreated irrigation water to meet rising food demands has significantly contributed to the development of salt-affected soils. Salinity may be primary or secondary based on the source of salts. Primary salinization results from natural processes such as rock weathering, capillary rise of shallow groundwater, seawater intrusion in coastal areas, and deposition of salt-laden sand by sea winds. In contrast, secondary salinization is mainly caused by anthropogenic activities, including the use of poor-quality irrigation water, discharge of industrial effluents, excessive application of basic fertilizers, flooding with saline water and improper planning of developmental activities.

Classification of Salt-Affected Soils

According to soil salinity staff (1954), USDA system of classification, there are three categories of salt-affected soils i) saline ii) sodic iii) saline-sodic.

I) **Saline Soils** – Soils containing a sufficient amount of neutral soluble salts that have adverse effects on the normal growth and development of plants. These soluble salts are chiefly composed of chlorides and sulfates of sodium, calcium, and magnesium. While a little concentration of cations like K+, NH4+, and anions like NO3-, and BO3-3 occur in these soils. Saline soils have ECe ≥ 4 dS m1, pHs < 8.5, ESP < 15 and SAR < 13 (mmol $L^{-1})^{1/2}$.

II) **Sodic Soils** – Soils containing adequate amounts of carbonates (CO3-2) and bicarbonates (HCO3-) of sodium that have a serious impact on plant normal development. Sodic soils have ECe < 4 dS m-1, pHs >8.5, ESP > 15, SAR > 13 (mmol $L^{-1})^{1/2}$.

III) **Saline–Sodic Soils -** Soils containing both soluble salts of chlorides and sulfates of sodium as well as carbonates and bicarbonates of sodium which are capable enough to cause harmful effects on plants. Saline-sodic soils are characterized as soils that have ECe > 4 dS m-1, SAR > 13 (mmol $^{L-1})^{1/2}$, and ESP > 15. The pHs is variable as it depends upon the concentration of salts.

In older literature, the term alkali is used in place of sodic while saline–alkali is in place of saline–sodic. The use of the term alkali is being discouraged because of its ambiguity with the term "alkaline" which generally refers to soils having pH > 7.0.

Impacts of Salt-Affected Soils

The salt-affected soils have a detrimental effect on the physical, chemical, and biological properties of soils.

Physical Properties

Elevated exchangeable sodium deteriorates soil structure by reducing pore space and impairing soil–water and soil–air retention. Slaking, clay swelling and particle dispersion cause aggregate breakdown, lowering hydraulic conductivity and infiltration. Structural degradation and reduced air–water transmission lead to hardpan formation, creating unfavorable conditions for plant establishment and growth.

Chemical Properties

High salinity and sodicity of salt-affected soils suffer from deficiencies of nitrogen (N), phosphorus (P) and potassium (K). High pH also adversely affects the availability of micronutrients such as Iron (Fe), Zinc (Zn), Copper (Cu), and Manganese (Mn). Due to salt toxicity, high osmotic suction and degraded soil structure result in poor vegetation growth which ultimately leads to low carbon inputs as well as a high loss of organic matter.

Biological Properties

High salt concentration causes osmotic stress and dehydration of microbial cells that significantly reduce the microbial population and its enzymatic activities with a role in carbon, nitrogen, phosphorus, and sulfur cycles.

Reclamation and Management of Salt-Affected Soils

Scientists worldwide use two main strategies to manage salt-affected soils: fighting with salt and living with salt (ICARDA). Fighting with salt involves reclamation through physical methods (scraping, flushing, leaching, drainage) and chemical amendments (gypsum, phosphogypsum, $CaCl_2$, sulfur, acids, Fe and Al sulfates). As these methods are costly and cumbersome, the eco-friendly **living with salt** approach is gaining importance, with phytoremediation emerging as a cost-effective and sustainable biological solution for adapting plants to saline soils.

Phytoremediation

Phytoremediation, a term coined by Ilya Raskin of Rutgers University, USA, derives from the Greek *phyto* (plant) and Latin *remedium* (restoring balance). It is a plant-based approach for reclaiming salt-affected soils by using plants to absorb and reduce salt concentrations and soil contaminants through their root systems, thereby improving soil fertility and stabilizing the rhizosphere ecosystem (Ali et al., 2013; Jacob et al., 2018; Dalcorso et al., 2019).

Criteria of Selection of plants used in Phytoremediation

Plant species suitable for phytoremediation of salt-affected soils should exhibit rapid normal growth, high biomass production, deep root systems, efficient salt or contaminant extraction, high water uptake capacity, adaptability to local soil and climate conditions, and ease of planting and maintenance.

Mechanism of Phytoremediation

Generally, two defense strategies are adopted by plants to cope with salt toxicity namely, avoidance and tolerance.

Avoidance

Avoidance is the primary extracellular defense mechanism in plants, involving restriction of ion uptake and movement into tissues through root sorption, ion precipitation, exclusion, and embedding. Under salt stress, plants initially immobilize ions via sorption or chemical modification. Root exudates, including amino and organic acids, act as ligands that complex ions in the rhizosphere and alter pH, promoting ion precipitation, reducing bioavailability, and minimizing toxicity. Ion exclusion operates through barriers between roots and shoots, limiting ion transport from soil to aerial parts (Dalvi, 2013). Ion embedding involves binding of positive ions to carboxylic groups of polygalacturonic acids in cell wall pectates, restricting their entry into plant cells (Ernst et al., 1992).

Tolerance

Once salt ions enter the plant cytoplasm, plants activate intracellular defense mechanisms such as ion inactivation, chelation and compartmentalization to reduce toxicity. Various organic and inorganic ligands chelate ions; organic compounds including organic acids, amino acids, proteins, polyphenols, phytochelatins and metallothioneins bind free ions and lower their bioavailability. The resulting complexes are transported to inactive compartments like vacuoles, leaf sheaths, petioles and trichomes for sequestration, protecting metabolically active tissues. Subsequent leaf shedding further removes toxic ions. Major phytoremediation mechanisms include phytoextraction, phytostabilization, phytotransformation, phytovolatilization and phytofiltration.

Phytoextraction

The use of plants to take up salts from the soil, translocate and accumulate those salts in their aboveground biomass (Jacob *et al*., 2018). The process of phytoextraction of salts includes a few steps: (i) mobilization of salts in the rhizosphere (ii) uptakes of salts by plant roots (iii) translocation of salts from roots to aerial parts of plants (iv) sequestration and compartmentation of ions of salts in plant tissues (Ali *et al*., 2013). The key factors that determine the potential of phytoextraction are hyperaccumulators and aboveground mass.

Phytostabilization

The use of salt-tolerant plant species to immobilize salts around the root and decrease their bioavailability, thereby preventing their migration into the plant ecosystem (Wong, 2003; Marques *et al*., 2009). The main advantage of this mechanism is the disposal of salt-rich biomass is not required (Wuana and Okiemen, 2011).

Phytotransformation

The breakdown of highly toxic salt ions taken up by plants into less toxic salt ions through the different metabolic processes.

Phytofiltration

The use of plant roots (rhizofiltration), shoots (caulofiltration), or seedling (blastofiltration) to remove the salt ions from contaminated soils as well as contaminated waters. Rhizofiltration is the most common and effective type of phytofiltration where salt ions are either adsorbed onto the root surface or absorbed by the roots. The root exudation can change the pH of the rhizosphere, which leads to the precipitation of ions on plant roots (Javed *et al*.,2019)

Phytovolatilization

The phytoremediation strategy uses the plant to take up salts from the soil, convert these toxic ions into less toxic volatile forms, and subsequently release them into the atmosphere by plant transpiration through leaves.

Advantages of phytoremediation

Phytoremediation is a cost-effective approach for large-scale soil remediation, as it involves only the initial planting cost compared to physical and chemical methods. It efficiently extracts harmful ions (Na^+, Cl^-, SO_4^{2-}) and heavy metals from deeper soil layers, increases organic matter, enhances microbial activity, prevents salt leaching into groundwater, and sustainably improves environmental quality.

Limitations of Phytoremediation

Phytoremediation is a slow process, often requiring several years, especially in moderately to highly contaminated soils. Disposal of salt-rich plant biomass after remediation is tedious. Pollutants may persist through phytovolatilization, contaminating air and redepositing via precipitation. High salinity hampers seed germination and early growth, limiting biomass cover and large-scale application. Plants are also vulnerable to pests and pathogens, and the toxicity and biodegradability of contaminants are not fully understood. As phytoremediation is site-specific and influenced by soil and climate, improving plant performance is essential for effective remediation.

CONCLUSION

Salt-affected soil is a vital issue for soil health and its quality, agricultural production as well as food security due to the toxic effects and rapid accumulation of salt ions in the soil environment. To prevent or mitigate the contaminants phytoremediation has been proven to be a promising technique for the revegetation of moderately and heavily contaminated soils with good public acceptance. Phytoremediation is a cost-effective non-conventional method and has several advantages for the reclamation of salt-affected soil compared to other physiochemical techniques. Phytoremediation has vast potential to bring back the productivity of the soil. Nowadays the price of chemical amendments and their aftereffect is increasing so phytoremediation becomes an alternative, viable, and low-cost ecofriendly approach with significant improvements towards sustainability of soil, environment, and ecosystem restoration.

The way forward and Future prospects

Although much remains to be studied and no single approach is sufficient for remediating salt-affected and contaminated soils, integrating genetic engineering, microbe-assisted, chelate-assisted, and physicochemical methods with phytoremediation is essential for effective soil stabilization and restoration.

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