Haloremediation for Amelioration of Salinity

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Abstract

Soil and water salinization is a major problem today. Many crop species do not tolerate this condition. The use of halophytes to remove salt from the soil and water is an emerging strategy. Environmental remediation using biodiversity has been widely used because it is a low cost and easy management technique, compared to chemical and physical amelioration options. Halophytes are tolerant plants capable to accumulate and/or exclude salts using different mechanisms. These plants have anatomical and physiological adaptations as well as fast metabolic responses to promote osmotic adjustment and avoid saline stress.

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This approach is evolving as salt tolerance as "halophytoremediation." The species used may belong to different families and genera because they have different tolerance mechanisms.

This chapter deals with (a) what are halophytes, (b) salient information about halophytes, (c) why do we need halophytes, (d) what are the threats for halophytes, (e) how to protect and conserve halophytes, and (f) how salinity tolerant plants can be used to remedy saline soils by allowing food to be grown in these areas in the future.

Keywords

Salinity · Phytoremediation · Phytotechnology · Halophytes · Salt-affected soils · Brine concentrating plants

1 Introduction

Increasing salinity in soils and water is a major problem today, as many crop species cannot tolerate this condition. Salt-affected soils can be grouped into saline soils, sodic soils, and saline-sodic soils (Brady 2002). Almost 40% of salt-affected soils in the world are saline and 60% are sodic (Qadir et al. 2006; Tanji 1990). Saline soils are distinguished by the large content of soluble salts, sodic soils with higher levels of sodium ions, and saline-sodic soils with an excess of salts and exchangeable sodium (Sastre-Conde et al. 2015). Different engineering-based remediation techniques have been developed over the last few decades to treat contaminated sites. Finding an appropriate remediation strategy is a difficult task. The most popular ones are (a) immobilization technologies (using barriers, reducing permeability and solubility), (b) toxicity reduction technologies (chemical treatment), and (c) separation/concentration technologies (soil removal, soil flushing, and electrokinetic extraction) (Mulligan et al. 2001). The high cost of these technologies was one of the obstacles, which delayed their worldwide adoption. The use of halophytes and salt-tolerant plants to remove salt from the soil is a strategy that is currently being used, because it is a low cost and easy management technique. These plants are able to accumulate and exclude salts by different mechanisms. Halophytes have anatomical and physiological adaptations as well as rapid metabolic responses to promote osmotic adjustment. From the point of view of phytoremediation, based on their salt tolerance, halophytes can use distinct mechanisms such as exclusion, accumulation, and conduction. Excluders prevent salts from entering their tissues as a salinity tolerance mechanism; accumulator uptake and accumulate salts in their tissues and the third type, called conductor plants, absorb salts and excrete them by salt glands, conducting salts from the soil into the air (Jesus et al. 2015). The species to be used by haloremediation may belong to different families and genera; they have different tolerance mechanisms, and therefore can be used in combination with remedy soil salinity and allow the cultivation of food (Fig. 1).

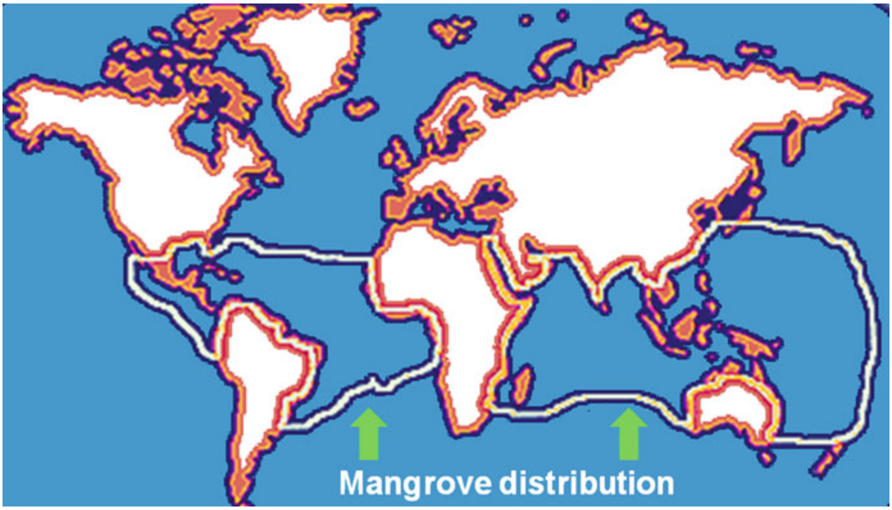


Fig. 1 Halophytes are distributed on all the world's continents except Antarctica. Mangroves, for example, are found in tropical areas only within the 20 °C isocline (white line)

2 Sources of Salinity

In arid and semi-arid regions, soil salinity is a common phenomenon and salinization often derives from a natural process. In general, soluble salts can be added to the earth crust by three main sources: marine, lithogenic, and anthropogenic, contributing more or less to soil and interstitial water salinization (Waisel 1972).

3 Marine and Lithogenic Sources

Coastal regions receive a large supply of salts from the oceans. The salts present in seawater are brought by winds to the continent (Fig. 2). Then they return to the ocean by draining the soil. This process is called cyclic salts. Seawater can also provide salts through local groundwater, which eventually can affect aquifers (Waisel 1972). Another way to add soluble ions to soils is through volcanic eruptions. This process contributes to large amounts of soluble chlorine and sulfur that will be deposited in the soil through precipitation. In terms of geological processes, other nutrient cycles contribute to the increase of salts in soils. Some rocks are naturally composed of large amounts of alkali metal hydrochlorides and with weathering these elements become available to the environment, the limestones, sandstones, and dolomites can be cited as examples.

Fig. 2 Salt pans and salt production in coastal zone

4 Anthropogenic Sources

Human activities have contributed massively to the amount of soluble salts in soils, especially in arable areas. Indiscriminate use of fertilizers, intensive irrigation and the use of low quality water are the main causes of salinization. In arid and semi-arid regions of extensive agriculture, ever-longer drought periods further contribute to the increase in salts available in the soil as soil evaporation rates are higher and bring more surface-level salts. It is estimated that 1–10 billion hectares of soil are affected by high salinity and that this damage can increase by 10–16% per year in about 100 countries (Qadir and Oster 2004). Industries are an important source as well, as they release large amounts of airborne substances that, at some point, are precipitated through rainfall and reach the ground as soluble ions. The fact that the presence of salts in high soil concentrations affects agricultural production and for some non-tolerant native species may represent a high selective pressure.

5 Saline and Sodic Soils

It is important to highlight that soils may undergo salinization due to excess of different salts. When large amounts of sodium accumulate, this soil is considered sodium and there is a large amount of NaCl present, for example. Contrastingly,

Table 1 Categories of salt affected soils and associated problems. *EC* electrical conductivity, *ESP* exchangeable sodium percentage

EC (mmhos cm^{-1})	ESP (%)	pH	Soil classification	Soil and plant response
<4	<15	<8.5	Normal	No osmotic stress; well aggregated
<4	>15	>8.5	Sodic	No osmotic stress; dispersed
>4	<15	<8.5	Saline	Osmotic stress; well aggregated
>4	>15	>8.5	Saline-Sodic	Osmotic stress; potentially dispersive

there are soils with high concentrations of potassium, calcium, magnesium, chlorine, and sulfur. Gypsum may also be responsible for soil salt content in a local scale. Saline soils usually have distinct ions and large amounts of sodium and therefore are considered saline-sodic.

There are different classifications for saline soils according to morphology, chemical composition, and electrical conductivity (EC) and exchangeable sodium percentage (ESP) (Waisel 1972) (Table 1):

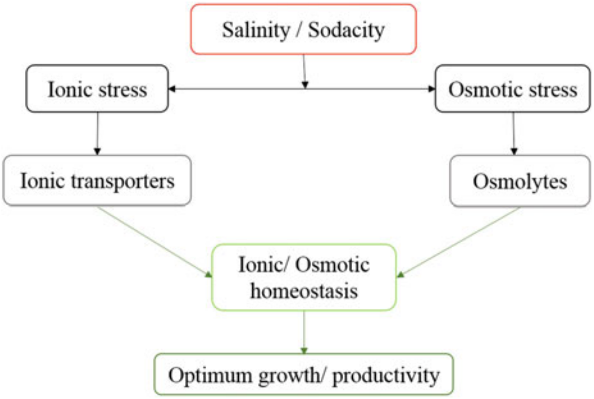
- **Normal soils**: Saturated extract of such soil present EC below 4 mmhos cm^{-1}, pH below 8.5, and ESP below 15%.
- **Sodic soils**: Soils with enough adsorbed sodium to inhibit growth of most agricultural crops. Usually, pH is above 8.5 and conductivity can be below 4 mmhos cm^{-1}. If it is a non-saline alkali soil or above these values if sodium percentage exchangeable is 15% or more. Soils like that frequently present gypsum in considerable amounts.
- **Saline soils**: The soluble salt content is high enough to inhibit growth of most agricultural crops. Electrical conductivity of the saturated extract of such soil is above 4 mmhos cm^{-1}, pH = is below 8.5, and exchangeable sodium is below 15%.
- **Saline-Sodic**: Present EC above 4 mmhos cm^{-1}, the ESP is above 15% and the pH is above 8.5.

Salt excess in soils can bring drastic changes in some of the soil physical and chemical properties resulting in the development of an environment for growth of most crops (Fig. 3).

6 Effects on Plants

Most plants, especially used in agriculture, are not salinity tolerant. When in high temperatures and salts in the soil, these plants exhibit physical changes, such as stoma closure, osmotic shock, inhibition of cell division and photosynthesis, nutrient absorption imbalance, reduction in osmotic potential, and signs of toxicity of applied ions such as Na^+ and Cl^-, resulting in inhibition of plant growth or death (Flowers et al. 2015). The presence of soluble salts, especially the adsorbent ones, contributes

Fig. 3 Influence of salinity and sodacity on plant growth



to soil degradation, destabilizes soil aggregation, and increases dispersion dynamics, especially in clay aggregates, reduction of soil hydraulic conductivity, damage or movement of air and water with consequent effect on runoff and erosion exposure. These effects on soil stability are shown as lower water availability for plants and lower root penetrations, oxygen content, and seedling emergence (Qadir et al. 2006).

7 Salt Stress Imposition on Plant Physiology, Growth and Development

The effect of salinity may be physiological, biochemical, or anatomical (Murtaza et al. 2017). Growth at all stages reduces by the presence of salts in root zone (Tuna et al. 2008) and less movement of reserved food (Nuttle et al. 2000), disturbance in osmotic pressure, by damaging the hypocotyls and leaf cell expansion (Song et al. 2008). High concentration of salts inhibit water uptake by plant roots (Munns and Tester 2008) and deteriorate permeability of plasma membrane (Murphy et al. 2003), stop photosynthetic activity by unbalancing turgor and osmotic potential, and eventually death of leaf tissues (Ibrahim 2016; Alzahrani et al. 2018).

Under various salinity levels, stunted growth has been observed in many crop plants (Pessarakli et al. 2017; Ahmad et al. 2013). Elevated salt stress induces changes in plant growth and metabolic processes and disturbs activities of antioxidant enzymes, generation of ROS, and degradation of photosynthetic apparatus. Reduced maize growth under salt stress is mainly due to deteriorated photosynthetic activity of the plant (Murtaza et al. 2017).

Plants have well-established antioxidant defense system comprised of antioxidant enzymes (SOD, CAT, POD, APX, and GR) (Miller et al. 2010) which scavenge ROS within plant cells (Choudhury et al. 2017). Under salinity stress the production of ROS would increase (Iglesias et al. 2015).

The highly cytotoxic ROS can cause damage to membrane proteins and lipids and disrupt normal plant metabolism. Azevedo Neto et al. (2004) reported increased activities of antioxidant enzymes under saline environment when compared to control and this increase was more pronounced in salt tolerant hybrids as compared to susceptible ones. Increased translocation of Na^+ from roots to stem and reduced K^+ concentration was reported with increasing NaCl in the growth medium (Dogan et al. 2010; Hakim et al. 2010). A number of studies exhibit that when subjected to salinity, plant water contents are drastically reduced. Different plant species respond divergently to tolerate salinity stress (Negrão et al. 2017).

8 Phytoremediation

Phytoremediation is a process that uses plants to promote decontamination, being able to absorb, accumulate, metabolize, volatilize, or stabilize inorganic and organic pollutants present in soil, air, water, or sediments. Based on its mechanism we can classify phytoremediation in (Fig. 4):

- **Phytoextraction**: This process works through the absorption of inorganic elements, including root contaminants. They can be used for contaminants such as metals (Cd, Ni, Cu, Zn, Pb), and can also be used for inorganic compounds (Na and Se) and organic compounds. Some plant species that can be used in the phytoextraction technique are *Alyssum bertolonii*, *Aeolanthus biformifolius*, *Thlaspi caerulescens*.
- **Phytostabilization**: In this case, organic and inorganic pollutants are incorporated into the lignin of the plant wall or soil humus.
- **Phytostimulation**: Growing roots promote the proliferation of degradation microorganisms in the rhizosphere, which use the plant exudates metabolites as a source of carbon and energy.
- **Phytodegradation**: Organic pollutants are degraded or mineralized within plant cells by specific enzymes.

There is also the rhizofiltration that keeps the contaminant in the root and the phytovolatilization that removes the contaminant in the gaseous form.

Using phytoremediation, organic pollutants can be degraded in the rhizosphere zone or they can be taken up by the plant, then degraded, sequestrated, or volatilized (Shang et al. 2004). Inorganic pollutants cannot be degraded, but can be sequestrated or stabilized in harvestable vegetation, particularly for macronutrient remediation (Nouri et al. 2017).

9 Haloremediation

When tolerant crops or halophytes are used to promote the removal of excess ions from the soil, this process is called halophytoremediation. Halophytes have been observed to be interesting in the ability to grasp sodium chloride in their cell vacuoles. Some species can be used to desalinize and restore saline soils and

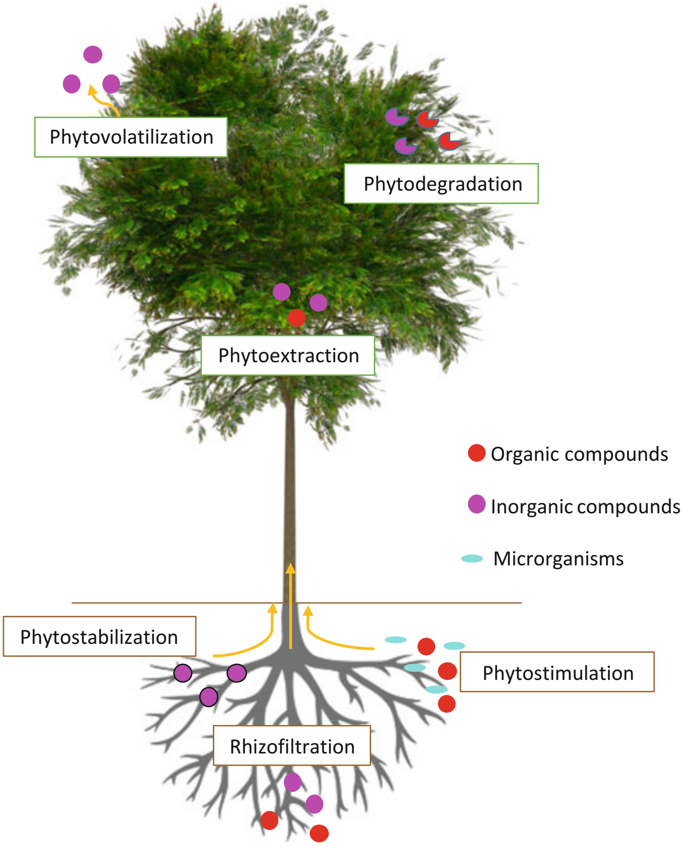


Fig. 4 Six main plant mechanisms can occur during phytoremediation to destroy, eliminate, transfer, or stabilize the environmental pollutants

withstand highly saline water irrigation (Wahla and Kirkham 2008). It was observed that rhizosphere desalinization is a result of shoot sodium accumulation. Halophytes can be used to leach salt from rhizospheres in regions where precipitation is too low (Rabhi et al. 2009). Cultivation of halophytes on salinized soil leads to marked absorption of sodium ions from roots and its accumulation in plant parts above the ground (Rabhi et al. 2010).

10 Halophytes

Plants capable of growing and completing their life cycle in environments with high salinity in the substrate are called halophytes.

Halophytes may belong to different botanical families and genera. Different classifications have been proposed to group them. Attributed to the NaCl content present in the habitat: *oligohaline* (0.01–0.1%), *mesohaline* (0.1–1.0%), and *polyhaline* (>1%). In accordance with their tolerance level the classification can be: *obligatory*, *preferential*, *supporting*, and *accidental halophytes*. In addition, these classifications may be more specific, however, by grouping species according to their salt regulation system:

1. *Euhalophytes:* plants that accumulate salts.
2. *Crinohalophytes:* plants that eliminate salts after absorbing then.
3. *Glycohalophytes:* plants that restrict salt accumulation.
4. Plants that accumulate and translocate salts to specific tissues doing phytoestabilization.

Halophytes have colonized distinct habitats such saline semi-deserts, mangrove swamps, marshes and sloughs, and seashores. Adaptation to saline environments by halophytes may take the form of salt avoidance or salt tolerance (Fig. 5).

11 Metabolism and Morphology of Halophytes

Halophytes have a set of morphological and metabolic adaptations to avoid and/or tolerate salt stress. Salt avoidance involves structural with physiological adaptations to minimize cell salt concentrations or physiological exclusion by root membranes. To avoid damage caused by excess salts, these plants can promote the exclusion, extrusion, and dilution of salts. Salt tolerance involves physiological and biochemical adaptations to maintain protoplasmic viability as cells accumulate electrolytes. As a tolerance mechanism, they can promote osmotic adjustment by synthesizing osmoregulatory molecules such as glycine betaine and proline; they can also synthesize hormones, especially abscisic acid (ABA) and perform detoxification through the activation of the antioxidant system, enzymatic and not enzymatic. In both cases, depending on the stress intensity, growth control occurs with a visible reduction in the size of plant organs (Fig. 6).

At the cellular level, these plants have photosynthetic adaptations to tolerate the toxicity of Na^+ and Cl^- ions to chloroplasts. They portion the toxic ions in leaves and halophytes are able to sequester ions in vacuoles and thus maintain the osmotic balance of cells. Succulent leaves have an aquifer parenchyma capable of storing large amounts of water, and under conditions of high salinity alter the thickness of the mesophyll, which may be larger or smaller depending on the species. These plants usually have lower stomatal density than glycophytes and some genera also present salt glands to exclude salt content. Finally, the flowering has an altered schedule to adjust to the short rain period.

Excreting salt glands distributed in numerous unrelated plant groups and some grasses, such as in cordgrasses (*Spartina alterniflora*, *S. patens*), alkali grass (*Puccinellia phryganodes*), saltgrass (Distichlis spicata), and shoregrass (*Monanthochloe littoralis*). In addition, a complex type of salt glands is known in *Frankenia* and *Tamarix*, and in mangroves species (*Avicennia* sp., *Laguncularia*

Fig. 5 Tropical mangroves (**a**) *Rhizophora* and *Avicinna* association, (**b**) *Sueda*, (**c**) *Rhizophora*

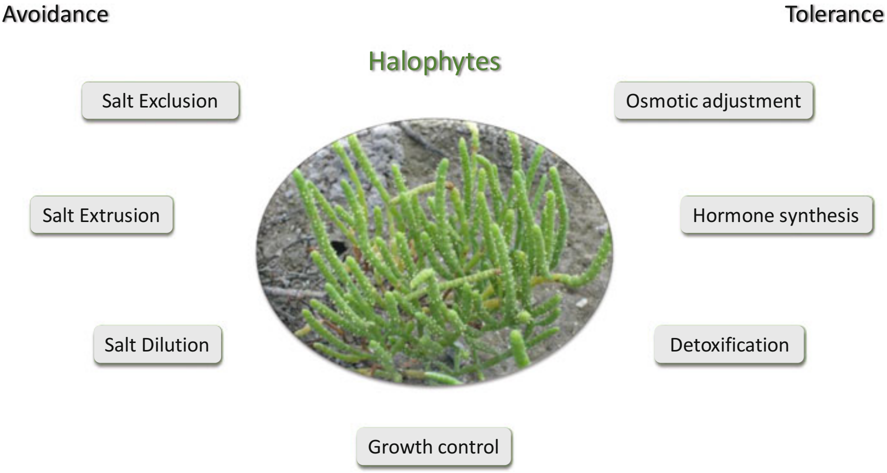


Fig. 6 Adaptation to saline soils by halophytes may take the form of salt avoidance or salt tolerance, for example, *Salicornia bigelovii*

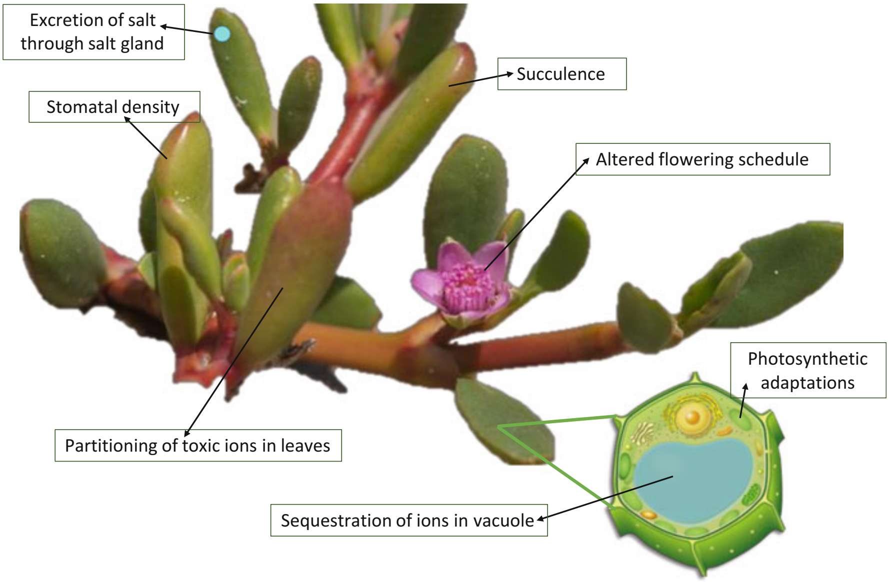


Fig. 7 Halophytes adaptations to survive under high salinity, for example, *Sesuvium portulacastrum*

racemosa). *Atriplex* (saltbush) has vesiculated trichomes and hairs on the surface of leaves. The leaves sequester excess electrolytes in the bladder cells, which release the salt back into the soil when they are ruptured. Additionally, *Atriplex* leaves have a silvery reflectance, due to the presence of this layer of trichomes, which has also been revealed to prevent some ultraviolet light from reaching the leaf tissues and therefore minimizing the development of reactive oxygen species (ROS) (Flowers et al. 2015) (Fig. 7).

12 Importance of Halophytes

Halophytes play an important role in protecting costal habitats and maintaining ecological stability. Some species are pioneers at the ecological succession and often act as sand dune makers (Willis et al. 2017). They prevent coast erosion, and protect against the force of the impact of waves, winds, and hurricanes. They also can promote succession in plant community on arid, semiarid, or hyper arid environment (Abdi and Afsharzadeh 2016).

Halophyte species represent a source of food and shelter for a large number of aquatic and terrestrial animal species (Feller et al. 2010). In addition, they have potential as fibers, fuels, green manure, as pharmaceuticals, industrial, and domestic. Studies have shown that many halophytes can be used as sources of nutritional grains and oils, while some have edible or economically useful roots, bark, stems, leaves, flowers, fruits, and seeds (Waisel 1972; Koyro et al. 2011).

Another important contribution is available for carbon sequestration (Glenn et al. 1992). Carbon fixed by vegetated coastal ecosystems (blue carbon) can mitigate anthropogenic CO_2 emissions. Nearly 242 ± 26 gC m^{-2} $year^{-1}$ are sequestrated by saltmarshes, 168 ± 36 gC m^{-2} $year^{-1}$ by mangroves, and 83 gC m^{-2} $year^{-1}$ by seagrasses (Taillardat et al. 2019).

Some halophyte species are able to accumulate, immobilize, transform, and excrete heavy metals (lead, cadmium, and selenium) from the soil (Lutts and Lefèvre 2015). They normally grow under stress condition (flooding or doughty, high light, and temperature) and with the presence of toxic ions (Na^+ and Cl^-). Some halophytes present salt glands in order to remove the excess of salt ions from their sensitive tissues by excretion processes. These anatomic structures are not specific to NaCl, and other toxic elements such as cadmium, lead, or copper are accumulated and excreted by salt glands or trichomes on the epidermis of the leaves (Manousaki and Kalogerakis 2011). Most species are able to absorb and accumulate toxic metals in roots and shoots (Ghasemi et al. 2018; Li et al. 2019).

Halophytes also can be used to remove salt from the soil, the biggest problem nowadays to agriculture and in the future.

13 Haloremediation of Saline Soils

Haloremediation has been attempted through biological reduction of salts that consisted of removal of high salt accumulating aerial plant parts. This approach was used by Chaudhri et al. (1964) in areas with negligible irrigation water or rainfall available for leaching. They used *Suaeda fruiticosa* Forsk for salt extraction from soil. This species, which has a very low irrigation requirement, is among the few plants that can grow in highly saline soils and it is capable of removing 1088 kg in 0.4 hectare (Chaudhri et al. 1964). Rabhi et al. (2009) observed the potential of *Suaeda fruticosa* and *Tecticornia indica* for soil desalinization in a greenhouse. One of the halophytes reported to be suitable for remediation of saline soils is *Suaeda salsa*, which can uptake the salt from soil and store it in plant tissue (Panta et al. 2016). In an experiment conducted by Rabhi et al. (2009), it was confirmed that the perennial species of halophytes when grown under saline soil and irrigated by tap water for 170 days, significant reduction in salinity is observed. The irrigation was carried out without any leaching. Soil electrical conductivity also decreased as the sodium ion concentration in soil decreased. *Sesuvium* sp. are most successful in soil improvement and are able to accumulate up to 30% sodium ion (Rabhi et al. 2009).

Ravindran et al. (2007) examined the performance of five fast growing herb species, namely *Suaeda maritima*, *Clerodendron inerme*, *Ipomoea pes-caprae*, *Heliotropium curassavicum*, and the tree, *Excoecaria agallocha*. The aerial organs of the plants were cut, dried, and analyzed after 120 days. *Suaeda maritima* and *Sesuvium portulacastrum* recorded the highest amounts of salt accumulation in their tissues, and therefore had the best performance in terms of desalination.

Halophytes can be used in constructed wetlands (Farzi et al. 2017). *Salicornia europaea*, *Salsola crassa*, and *Bienertia cycloptera* were able to grow well and

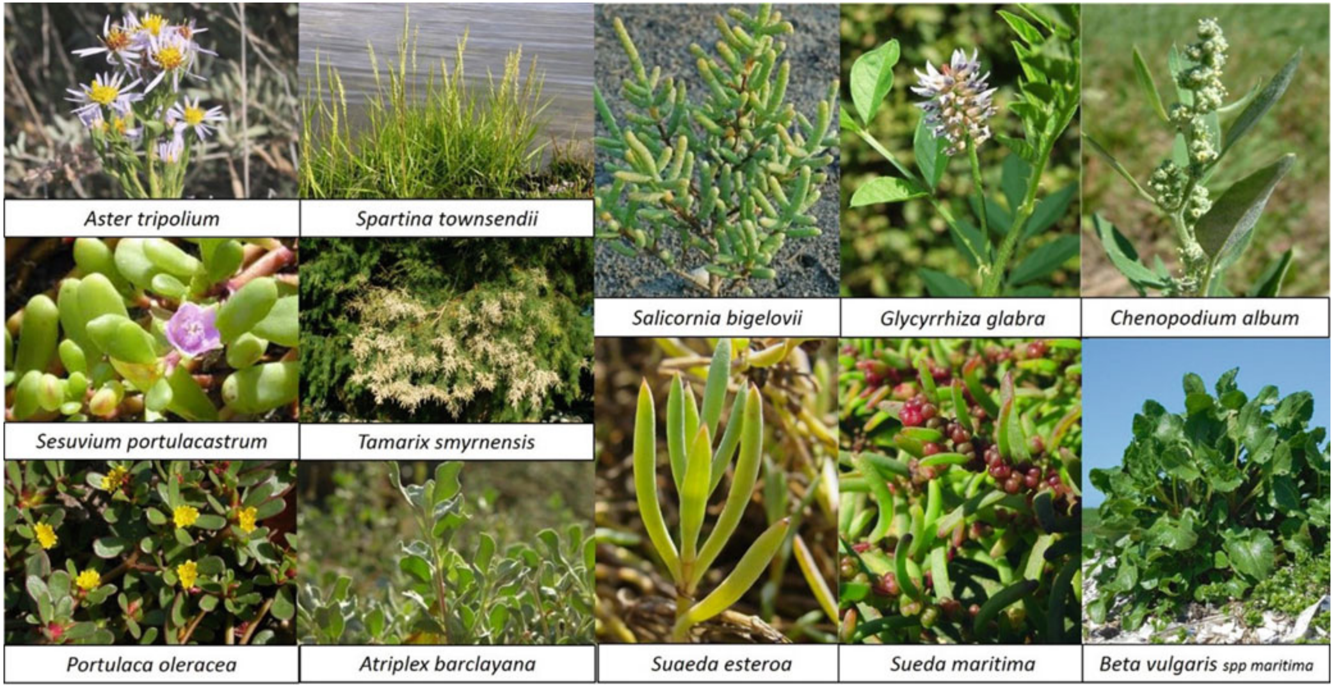


Fig. 8 Halophytes and salt-tolerant plant with potential to remove soil salinity

complete their life cycles at all the salinity levels [electrical conductivity (EC) » 2, 6, 10 dS/m]. Electrical conductivity and concentrations of calcium (Ca), magnesium (Mg), sodium (Na), and chlorine (Cl). Moreover, these plants reduced the measured parameters to acceptable levels.

Portulaca oleracea is salt-tolerant species that can be grown in saline soils for phytoremediation. An experiment proved that if the water table is 1.1 m, then the growth of *Portulaca oleracea* does not require any irrigation from any means and it removes the salt to the highest extent. Highest salt accumulation is observed to be 497 kg per hectare, which makes it around 16% of removed salt. The *P. oleracea* also has been used for hydroponic system removing and accumulating significant amounts of sodium and chlorine (De Lacerda et al. 2015). *Chenopodium album* species produce high dry biomass and proved that these species can be used as a rehabilitating and remediation agent for the saline soils. *Glycyrrhiza glabra*, commonly known as liquorice, is salt tolerant and has been used for phytoremediating saline soils (Kushiev et al. 2005). Positive benefits to soil have been obtained on the growth of this specie. Soil salt content on which *G. glabra* grows has been tested to show a steep decline of salt content. Abandoned soils can be brought back to life by the use of liquorice at low cost and in less time (Kushiev et al. 2005) (Figs. 8, 9, and 10).

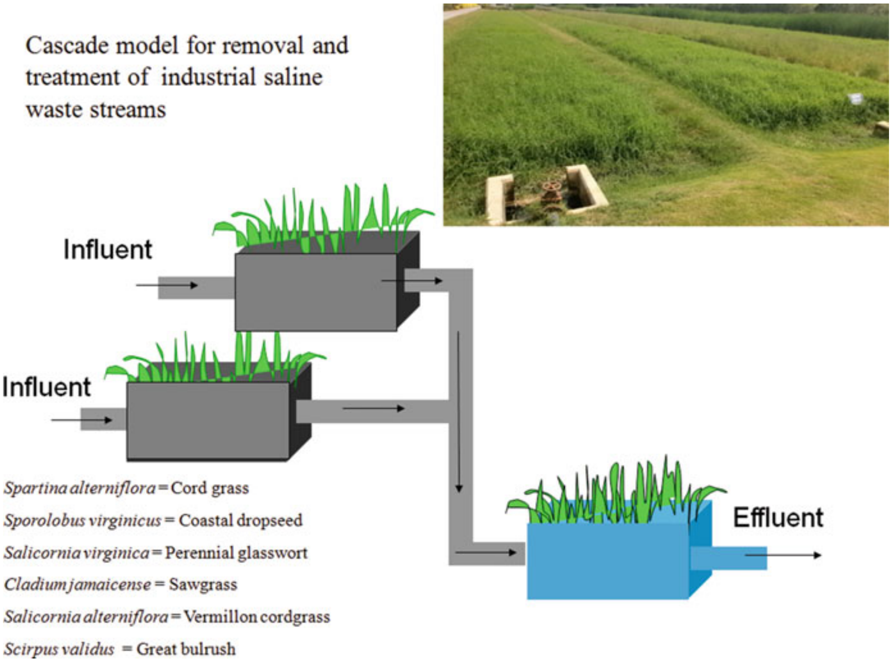


Fig. 9 Cascade approach for remediation of brine/industrial waste water containing salts

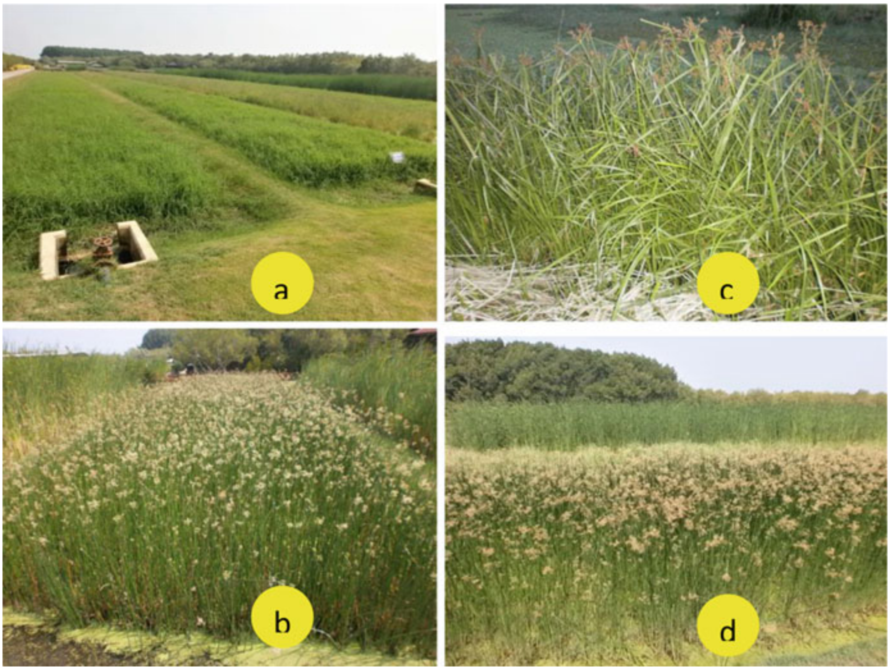


Fig. 10 Salt tolerant grasses and sedges for remediation of brine/industrial waste water containing slats

14 Conclusion

Application of haloremediation to control soil salinity is a very promising approach due to modern approaches in engineering-based remediation. Phytoremediation of salt-affected soils using halophytes has been studied and can be recommended as an efficient, inexpensive, and environmentally sustainable intervention in many areas of the world. Halophytes can adopt complex mechanisms, arising from genetic and environmental factors and physiological modifications, to cope with high levels of salinity. The selection of appropriate species according to the ecophysiological conditions of the environment as well as the methodology of cultivation helps this approach to be more efficient and economic. Plant species that can withstand high levels of salinity and produce a significant weight of biomass are usually preferred. Future research needs to improve the existing knowledge about the biological, physical, and chemical mechanisms associated with the application of halophytes for haloremediation and their effects on contaminated soils and waters. Such investigations will enhance the strategies of soil improvement by combining physical, chemical, and biological systems.

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