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Application of green remediation on soil salinity treatment: A review on halophytoremediation

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ABSTRACT

The salinity of soil and water resources is one of the economically expensive challenges to achieve sustainable development across the world. Salinity, which is a major environmental issue for both arid and semi-arid regions, is highly stressful for vegetation and adds to other stresses including water scarcity, nutrient deficiencies and soil alkalinity. Remediation is a strategy to clean up pollutants from the plant root zone in order to reduce vegetation stress and enhance productivity. This strategy involves biological management of soil and water which often leads to increased soil infiltration and leaching of excess salts out of the root zone. Several methods of soil and water remediation have been proposed that can be classified into the two main groups of engineering-based remediation and green remediation. Green remediation is the use of vegetation to remove or contain environmental contaminants such as heavy metals, trace elements, organic compounds and radioactive compounds in soil or water. There has recently been increased interest in green remediation using halophytes, particularly in developing countries. This paper reviews the different methods of phytoremediation and their application in green remediation. It also describes how halophytes are an emerging means of desalination and how they can be used for phytoremediation of heavy metals.

Contents

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1. Introduction

In the last two decades, the technology of green remediation was introduced and developed widely. Use of natural system processes such as bioremediation (using microorganisms to remove or neutralize contamination) and phytoremediation (using plants to absorb, remove or break down contaminants) are two main practices of green remediation (Flathman and Lanza, 1998; Frankenberger et al., 1989; Mejáre and Bülow, 2001). One of the drivers for the increased use of green remediation technologies such as phytoremediation and bioremediation is the relatively low cost technology compared to engineering-based remediation approaches (Pilon-Smits, 2005). The problems of soil salinity persists as the agricultural land expands shrinking the cattle grazing land and the encroachment of saline soil vegetation grazing has compounded to loss of vegetation and impacted the cattle health (Di Bella et al., 2014). It also results in the degradation of both wetlands and wildlife habitats (Wang et al., 2012). The soil salinity also impacts farm lands by effecting on germination of crops and as a result a decline in overall agricultural output including the organic carbon mineralization (Kim et al., 2012; Setia et al., 2011). For instance, there was a mild change in the chemical properties of rice grain character under mild salt stress but as the stress increased the stress was impacting on yield (Thitisaksakul et al., 2015).

Not only the soil salinity issues are we dealing in the modern economy but it is the water salinity that also is an integral part of salinity problem. Promoting long-term sustainable water management necessitates a progressive strategy of decreasing pollutant discharges to the environment. Wastewater systems with different sources of domestic, commercial and urban effluents, generate both organic and inorganic contaminants (Saha et al., 2014). Organic pollutants are mostly anthropogenic and are often toxic being released to the ecosystem. Inorganic pollutants not only originates as a natural phenomenon in the earth crust or atmosphere but also by human activities such as mining, agriculture or military activities that enhance the release of pollutants to the environment causing harm to natural ecosystems (Nriagu, 1979; Pilon-Smits, 2005).

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 (Bage et al., 2002). 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 electro-kinetic extraction) (Mulligan et al., 2001). The high cost of these technologies was one of the obstacles that have delayed their worldwide adoption. In 2003, it was estimated that annual environmental remediation costs were $8 billion in the US and around $50 billion worldwide (Tsao, 2003).

In green remediation strategies, different vegetation species with different properties are selected to enhance pollutant accumulation. Generally, plants need to be fast growing, tolerant to contaminants, of high biomass capability, and with higher phytoaccumulative behavior (Kopittke and Menzies, 2005). Agronomic activities, supplementary irrigation, fertilization, and genetic engineering are other alternatives to increase or manipulate the rate of plant uptake (Abedin et al., 2002; Negri et al., 2004). Vegetation uptake varies for organic and inorganic pollutants. For organic compounds, there is no membrane transporter in the plants, so pollutant movement is mainly through diffusion while for the inorganic pollutants, uptake occurs through biological processes and movement is by membrane transporter. Incomplete knowledge of these biological processes has resulted to limitations in application and efficiency of phytoremediation techniques. However, what is obvious is that higher bioavailability of pollutants and more contacts between plants and their microbes would enhance remediation efficiency (Pilon-Smits, 2005).

Bioavailability of pollutants is correlated with soil and plant conditions, chemical properties and biological activities of the contaminants, and environmental parameters (Petruzzelli et al., 2015). Clay soils with their higher soil moisture holding capacity than sandy soils have more binding opportunities for chemical ions present in organic matter (Nwoko, 2010). The movement of contaminants in the soil is influenced by their volatility and hydrophobicity. Pollutant volatility measures the ability of a contaminant to move in the water. Hydrophobicity shows how pollutants can be transferred from soil/water to the plant expressed in terms of the octal water partition coefficient ($\log K_{ow}$) (Barbafieri and Tassi, 2011).

Salts are naturally available in the soil and groundwater. Higher than natural levels of soluble salt in the soil or water can result in salinity with hazardous risks for plant health and productivity. More than 75 countries around the world are struggling with salinity problems (Alaghmand et al., 2016; Qadir et al., 2007). It is estimated that at least 20% of the irrigated lands in the world are affected by varying levels of salt (Qadir et al., 2008) and that this costs approximately US$ 12 billion per year in 1995 costs (Ghassemi et al., 1995). Desalinization of soils by halophytes was first suggested by Boyko (1966). Since then several studies have been conducted to investigate the possibility of saline soil reclamation using different species of halophytes (Honey-Rosés et al., 2014). Some of these studies also refer to other advantages of halophytes such as their potential as forage and oil seed crops. There are approximately one billion ha of salt-affected areas in the world (Yensen and Beil, 2006), these being mainly located in the Middle East, Central Asia, Northern Africa and Australia (Alaghmand et al., 2013; Alaghmand et al., 2015). This remarkably vast area provides a significant opportunity for halophytology.

2. Salt-affected soil categories

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) (Table 1).

Table 1 – Classification of salt-affected soils (after Brady, 2002).

Salt-affected soil classification	Electrical conductivity (dS/m)	pH	Sodium absorption ratio (SAR)	Soil physical condition
Saline	>4	<8.5	<13	Normal
Saline-sodic	>4	<8.5	>13	Normal
Sodic	<4	>8.5	>13	Poor

Increasing the osmotic pressure in salt affected soil may result in less accessibility to soil water content and an imbalance in the plants nutrient uptake (Adcock et al., 2006; Hogarth, 2015). The continuous increase of salt and/or Na^+ in salt-affected soils is often due to weathering of parent minerals or mismanagement of the land, water and vegetation resources.

Saline-sodic soils have several similar properties to sodic soils such as excess of sodium and impermeable structure; hence these two types of soils are usually grouped together and remediated using the same technology. Parameters for identifying sodic and saline-sodic soils include the content of Na^+ in the cation exchange complex or in the soil solution as well as salinity levels (Qadir et al., 2008).

Sodic soils may also be subdivided into alkali, black alkali, slick-spot or solonetz soils. The last of these has a high concentration of exchangeable Na^+. This has an adverse effect on plant growth and may cause surface crusting and hard setting. Sodicity can impact soil structure by specific physical operations such as dispersion of clays or slaking and swelling (Quirk, 2001).

2.1. *Effects of salinity on soil property*

The presence of salt in the soil helps the process of flocculation that consequently improves the soil physical properties such as stabilization and aggregation via soil aeration and root development. However, high salinity has adverse effects on soil fertility (Hogarth, 2015). Excess levels of sodium can separate and expand clay particles which in turn can cause soil swelling and dispersion. Soil dispersion often occurs through the regular wetting and drying of soil. During these processes, clay particles fill up the soil pores and decrease the permeability (Mohanty et al., 2015). The dispersed soil prevents water and air movement in the soil. The decreasing infiltration rate tends to restrict available water to the plants and also increases surface runoff. In effect, dispersed soil fills the macro pores, cracks, and fissures making the upper layer swollen and water logged. The soil structure is thereby decomposed and by decreasing the uptake of organic matter it loses its fertility. Concentration of high sodium levels also tends to produce surface crusting. When soil dries the dispersed clay particles make a hard surface layer which further limits movement of water into the soil (Warrence, et al., 2002).

However, other types of salt ions such as calcium and magnesium help soil flocculation. Therefore their concentration in the soil decreases the process of soil dispersion unlike sodium salts. The aggregation or dispersion of the soil depends on the relationship between soil salinity and sodicity and their combination in the soil (Rengasamy and Olsson, 1991).

2.2. *Effects of salinity on plants*

Salinity, water logging and inundation are major factors that affect plant growth. High water table levels in the dry periods of the year can be beneficial for vegetation roots because of upward capillary flow (Anand et al., 2015). However, this process may also bring up salts to the root zone from deeper soils (Aimrun et al., 2011). The concentration of salts in soils can occur in parallel with other plant stresses such as shortage of water, insufficiency of nutrients and soil alkalinity (Gorham, 1992; Marcelis and Van Hooijdonk, 1999) which can have adverse effects on plant growth (Kao et al., 2001; Lovelock and Feller, 2003). Soil salinity prevents the roots from drawing up water from the soil which consequently reduces the accessible water to the plant irrespective of the total water content of the soil due to difference in water potential leading

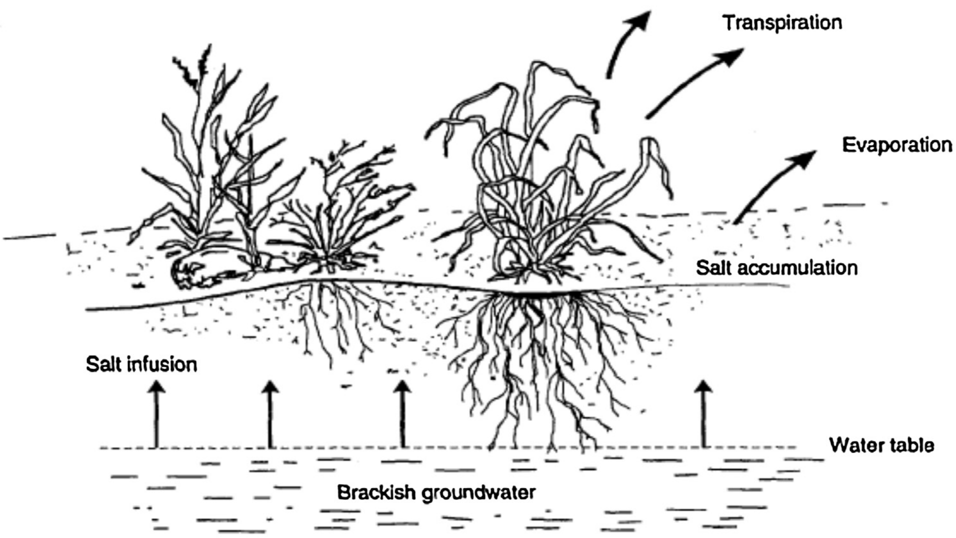

Fig. 1 – The process of water logging and salinisation (after Hillel, 2000).

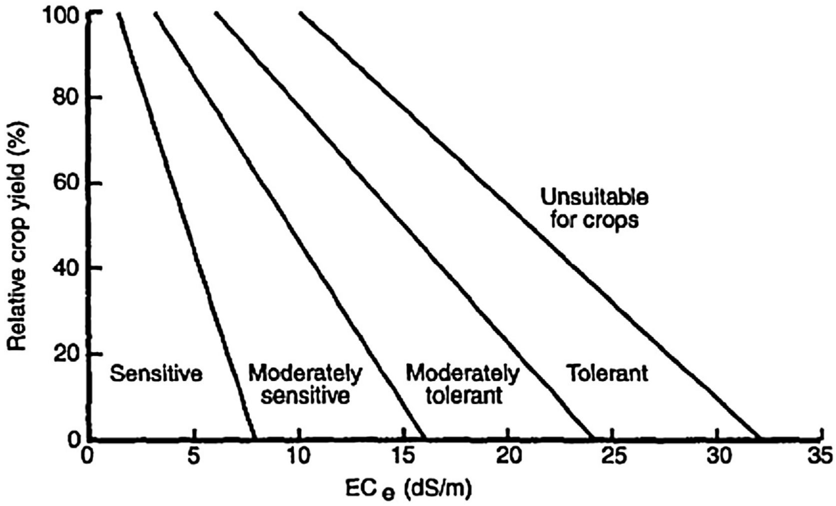

Fig. 2 – Crop tolerance to salinity (after Hillel, 2000).

to exosmosis (Macklon and Weatherley, 1965). In fact, plants then need more energy to extract water from the soil and this causes further plant stress. Several factors such as irrigation and climate may affect soil salinity. Irrigation can reduce the effect of salinity by increasing the available water and reducing the salt concentration in the soil solution in contrast to transpiration and evaporation which increase the salinity of the soil leading to increased plant stress (Fig. 1).

Different plant species have different responses to salinity depending on their (Colmer et al., 2005; Nouri et al., 2012; Nouri et al., 2013a,b). Four groups have been defined, namely sensitive, moderately sensitive, moderately tolerant and tolerant (Fig. 2). Generally the threshold of soil salinity is signified by an electrical conductivity (EC) level of 4 dS/m. However, when the soil EC exceeds 2 dS/m plant growth can still be adversely affected (Hillel, 2000). Hence the major focus is on halophytes to review innovation on green remediation technology at this juncture.

3. Soil remediation prospects

Soil remediation is a strategy that is employed to control salinity and sodicity in the plant rhizosphere in order to reduce plant stress and enhance productivity (Hogarth, 2015; Mohanty et al., 2015). This strategy involves the management of soil by increasing soil infiltration of water, lowering the water table or leaching excess salt out of the root zone. Several methods of soil remediation have been proposed including physical and chemical remediation (engineering-based techniques), bioremediation and phytoremediation (green remediation) (Fig. 3) (Singh and Ward, 2004).

There are four soil remediation techniques namely bioremediation, phytoremediation, physical remediation and chemical remediation (Singh and Ward, 2004). These techniques are applicable based on the intensity and area of impact of salinity in soil as well as in water. Mostly the bioremediation is treating salts and escaping its impacts by using different strains of bacteria (Cheng et al., 2012). The physical remediation is mostly the engineering based process and the chemical remediation also is a means of using various amendments suitable for smaller areas and usually costly affair (Diacono and Montemurro, 2015; Tejada et al., 2006). The use of plants to remediate the saline soil is called phytoremediation which is a natural healing process suitable for larger areas (Van Oosten and Maggio, 2015).

4. Green remediation overview

Physical and chemical approaches to soil remediation in terms of salinity and sodicity are effective but they can be expensive and may also complicate the actual process (Qadir et al., 2015). Green remediation approaches such as bioremediation and phytoremediation are generally seen as being more sustainable in terms of conserving natural resources (Ahmad et al., 1990; Kumar and Abrol, 1984; Tsao, 2003).

Recently the use of phytoremediation has become more widespread subject of interest to researchers and stake holders. Phytoremediation is a set of plant-based bioremediation technologies that use various species of living plants to clean up contaminated soils, water and air (Frick et al., 1999; Ghosh and Singh, 2005). 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.

Six main plant mechanisms can occur during phytoremediation to destroy, eliminate, transfer, or stabilize the environmental pollutants. Phytoremediation can therefore be categorized into these six processes, namely phytostabilization, phytostimulation, phytoextraction, phytovolatilization, phytohydraulics and phytodegradation (Fig. 4) (Mueller et al., 1999; Pilon-Smits, 2005).

Some of the amazing salt tolerant and remediating plants are *Sesbania bispinosa, Leptochloa fusca*, (Qadir et al., 2002), *Suaeda maritime, Sesuvium portulacastrum* (Jesus et al., 2015; Ravindran et al., 2007).

4.1. *Phytostabilization*

Phytostabilization or phytosequestration is a process to immobilize organic and inorganic pollutants within the rhizosphere zone through root absorption, erosion or leaching, or conversion of contaminants to less bio-available types. A native Australian *Carpobrutus rossii* (Gehrig et al., 2012) is an example of a resilient plant having a high phytostabilization potential. A mix of the trees and grasses is favorable for phytostabiliza-

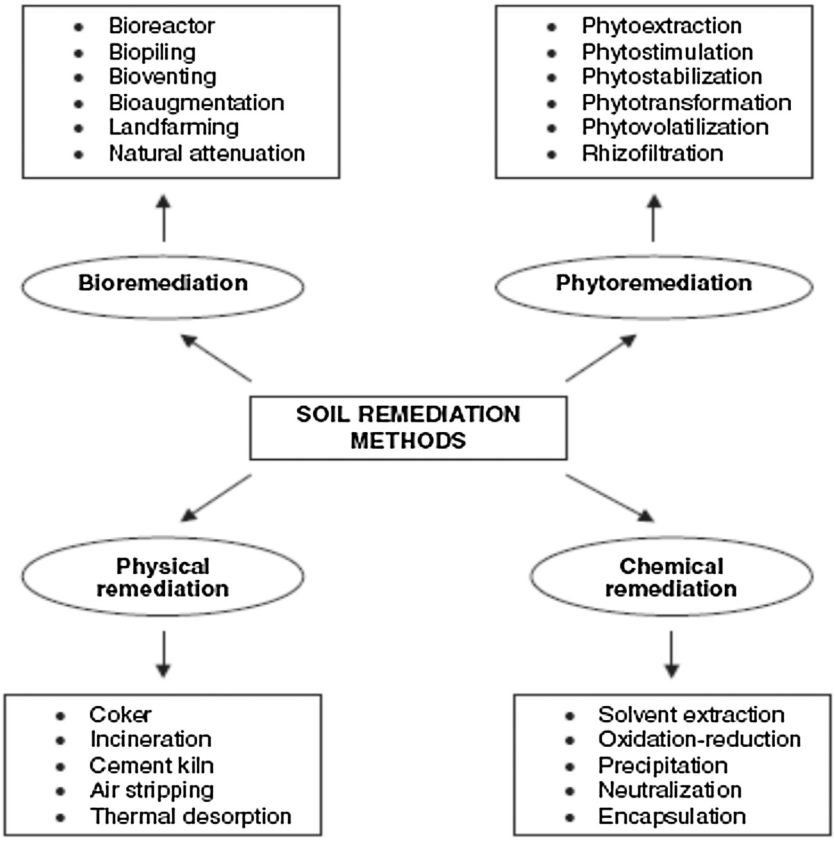

Fig. 3 – Different methods of soil remediation (after Singh and Ward, 2004).

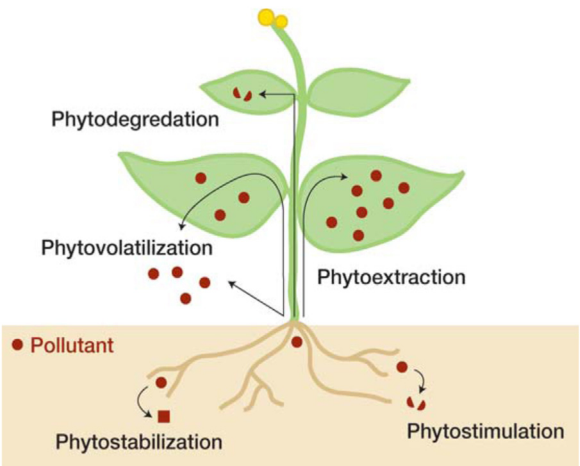

Fig. 4 – Phytoremediation processes (after Pilon-Smits, 2005).

tion. The deep roots and dense canopies of high transpiring trees will maintain an upward stream to avert the downward leaching whereas the dense rooting system of grasses eliminates erosion and lateral runoff (Alvarenga et al., 2009; Pilon-Smits, 2005). This method can enhance soil fertility as well. Phytostabilization is more applicable for larger sites with low rates of pollution and application should be limited in the food chain due to the possibility of contaminants translocating to the leaves. The main shortcoming of phytostabilization is the accumulation of contaminants in above ground parts. This needs regular monitoring to ensure that a stable condition is maintained. In addition, a high concentration of stabilized contaminants may prevent vegetation growth and decrease the bioavailability for phytoextraction due to sequestration with organic matter (Bolan et al., 2011).

4.2. *Phytostimulation*

Increasing the microbial activity of vegetation in the rhizosphere to clean up organic contaminants is called phytostimulation or rhizodegradation. Plants with large, dense rooting systems are more favorable for phytostimulation because of the high levels of microbial degraders in their roots (Lu et al., 2011; Pilon-Smits, 2005). Furthermore, such large and dense rooting systems with high microbial activity provide a suitable niche for microorganisms to live in the soil. It is generally considered that phytostimulation remediation sites should have low levels of pollutants that are not toxic for the selected species. The fungi *Trichoderma* sp. is an interesting plant that is involved in phytostimulation mechanisms by promoting the biotic as well as abiotic salt stresses (Contreras-Cornejo et al., 2015).

4.3. *Phytoextraction*

The process of pollutant uptake by roots, and the subsequent movement of pollutants to the above ground parts of plants is termed phytoextraction. One potential drawback of phytoextraction is the length of time to achieve desired level of remediation *Tamarix sp.* (Fig. 5) is a good example of a halophyte species that accumulates salts from soils in its aerial organs (Hassanli and Javan, 2005).

The risk of animals feeding on the above ground parts of the plant is another cause for concern for plants that extract contaminants. To be suitable for phytoextraction, vegetation species should have higher contaminant uptake and accumu-

Fig. 5 – Accumulation of salts from soil in Tamarix aerial organs.

lation rates in the harvestable plant materials to dispose of safely. Two of the most favored species are Indian mustard and sunflower (Niu et al., 2007; Pilon-Smits, 2005). These plants are mostly used to trap and clean up metals, radionuclides and toxic inorganics and should not be used for food purposes (Komárek et al., 2008; Sas-Nowosielska et al., 2004).

4.4. *Phytovolatilization*

Phytovolatilization involves uptake of pollutants, translocation and modification by the plant, and ultimate release to the air through the process of transpiration. This technique is used for organic and inorganic pollutants but organic ones mostly require degradation processes to become candidates for the volatilization (Davis and Erickson, 2002; Pilon-Smits, 2005). *Poplar sp*. are widely used for phytovolatilization due to their high transpiration rates.

4.5. *Phytohydraulics*

Deep rooted vegetation can uptake and degrade groundwater pollutants through their roots. The metabolism of phytohydraulics is based on the indirect remediation of groundwater through natural water pumping by tree root systems. Deep geotropic roots reach the contaminated groundwater, to draw out contaminants and clean the rhizosphere zone (Pilon-Smits, 2005; Sen, 2011). The plants like *Salix alba* can be used in treating the salty soils by phytohydraulics method (McCutcheon and Schnoor, 2004).

4.6. *Phytodegradation*

Phytodegradation or phytotransformation is the metabolic uptake and breakdown of organic pollutants and inorganic nutrients in the plant tissue by enzymes that convert pollu-

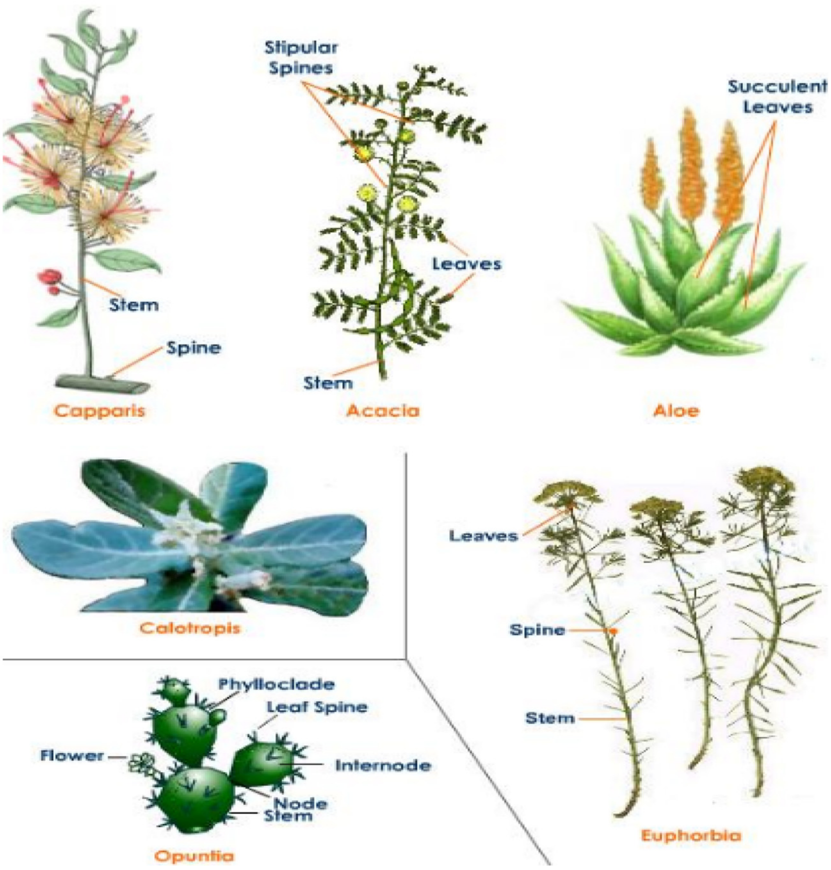

Fig. 6 – Ecological adaption by halophytes (http://www.tutorvista.com/content/biology/biology-iv/organisms-environment/ecological-adaptations-halophytes.php).

Fig. 7 – Carpobrotus rossii; a native salt tolerant plant of Australia growing in Brighton Le-Sands beach Sydney.

tants to harmless by-products. The most favorable species for phytodegradation are those that have large and dense rooting systems and those that produce an abundance of enzymes (Davis and Erickson, 2000; Newman and Reynolds, 2004; Pilon-Smits, 2005). The plants like *Sarcobatus vermiculatus* is used for phytodegredation due to its very high salt tolerance capacity (Waugh et al., 2011).

5. Halophytes adaptation to salt stress

In arid and semi-arid regions the amount of precipitation may not be adequate to leach out salts from the rhizosphere. Using halophytes that can accumulate salt would be an attractive alternative for soil remediation (Manousaki et al., 2013; Rabhi et al., 2009; Zakery-Asl et al., 2013). Halophyte functionality is not limited to salt remediation and can also be used for phytoremediation of heavy metals (Anjum et al., 2013; Eid and Eisa, 2010). Halophytes are usually native flora that can tolerate or even demand sodium chloride concentrations in the soil water of saline soils (Kefu et al., 2002). The survival of halophytes necessitates osmotic adjustment by using existing ions in the environment. For example *Atriplex amnicola* (River saltbush) has a steady response to salt levels. It can tolerate salinity upto 5 dS/m of salt concentration after losing half of its shoot biomass and cannot survive beyond 75 dS/m (Barrett-Lennard, 2002). The physiology of these plants allows accumulation of ions in order to retain plant growth while avoiding toxicity from either ion excess or water deficit (Flowers et al., 1986). Different species of halophytes with different habitat conditions have different strategies to survive (Fig. 6) (Watson and O'Leary, 1993).

Some xeric plants like opuntia have small scaly or spines leaves, thick cuticles and a multiple layered epidermis and sunken stomata to reduce evapotranspiration. Some halophytes like Capparis shed their leaves or keep water in their tissues during water scarcity. In such situations, photosynthesis is carried out by the green stems. Having long roots for extraction of deep water is another strategy that halophytes employ to survive in arid regions or in drought conditions. *Salicornia sp.* has specific mechanisms to resist against water shortage and soil salinity. Its thick skin and small surface area help reduce evaporation while an oxygen layer around the roots prevents the effects of salts and harmful metals (Santhanakrishnan et al., 2013). Fig. 7 shows Carpobrotus rossii (Haw.) Schwantes (Aizoaceae), an Australian native plant shows the potential of cadmium phytoremediation.

5.1. *Green remediation prospects of salt-affected soil*

Green remediation of salt-affected soil and water resources through cultivation of salt-tolerant crops may help decrease the global water shortage crisis as well as the limitation of land resources for agriculture (Glenn et al., 1998; Masters et al., 2007; Rogers et al., 2005). The extension of the currently available range of halophytes by classical breeding, biotechnology, tissue culture and plant exploration dates back decades. The process of halophyte agriculture expansion in the 21st century arose from the global crisis of water shortage. This prompted humans to improve the utilization methods of saline soils. A total of 10,000 salt-tolerant species have now been reported cultivation in a variety of climates and soil conditions (Yensen and Biel, 2006).

Some of the most popular salt loving species are *Atriplex halimus* (Vickerman et al., 2002), *Atriplex patula* (Krishnapillai and Sri Ranjan, 2005), (Naghd Abadi and Soroosh Zadeh, 2010), *Atriplex nummularia* (Edivan et al., 2010), *Portulaca oleracea* (Maas and Hoffman, 1977), *Chenopodium rubrum L.* (Warne et al., 1990), *Kochia scoparia* (Curtin et al., 1993), *Glycyrrhiza glabra* (Kushiev et al., 2006), *Allenrolfea occidentalis* (Zerai, 2007), *Borago officinalis* are some of the species that have been studied extensively. Domestication of halophytes is a potential approach for further extension of salt-tolerant crops (Colmer et al., 2005).

In terms of applications, Rhoades (1989) reported drainage water reuse in California as a sustainable approach for the disposal of saline waters. In the case, the appropriate species of halophytes for the reuse system had to be highly tolerant to salinity and sulfate toxicity as well as economically profitable (Grieve and Suarez, 1997). Rabhi et al. (2009) observed the potential of *Tecticornia indica* and *Suaeda fruticosa* for soil desalinization in a greenhouse. Later, Rabhi et al. (2010) evaluated the seasonal variations in the phyto-desalination capacities of these species in their natural biotope in Tunisia. They measured the shoot dry weights per tuft and per hectare taken from the inside and outside of the halophyte tufts. The results showed that electrical conductivity and soluble sodium content were significantly lower in the soil from inside the tufts compared to the surrounding soil. In the winter, electrical conductivity and soluble sodium content were 63–72% and 70.5% lower than outside, respectively. The *T. indica* showed a more efficient phyto-desalination capacity, regardless of the season. In *S. fruticosa*, roots exhibited a main role in soil desalinization by releasing sodium ions from the exchange sites to leach salts deeper from surface.

Cations can be classified as either acidic (acid-forming) are hydrogen and aluminum and common basic ones are calcium, magnesium, potassium and sodium. The cations lost or removed by plant roots or through leaching is resupplied by soils exchange sites to resupply. The higher the CEC of soil more it can supply called the soil buffer capacity (Mackenzie, 1951).

Agricultural practices on saline soils are problematic because of a low soluble source of Ca^{2+} and Mg^{2+} which can be found at different depths. During the process of cation exchange, the Ca^{2+} and Mg^{2+} are replaced with Na^{+} which releases the excess sodium ions. Leaching such soils by efficient irrigation will remove the released sodium ions from the root zone (Ozturk et al., 2006) (Fig. 8). The process of calcium exchange is similar to that of magnesium exchange.

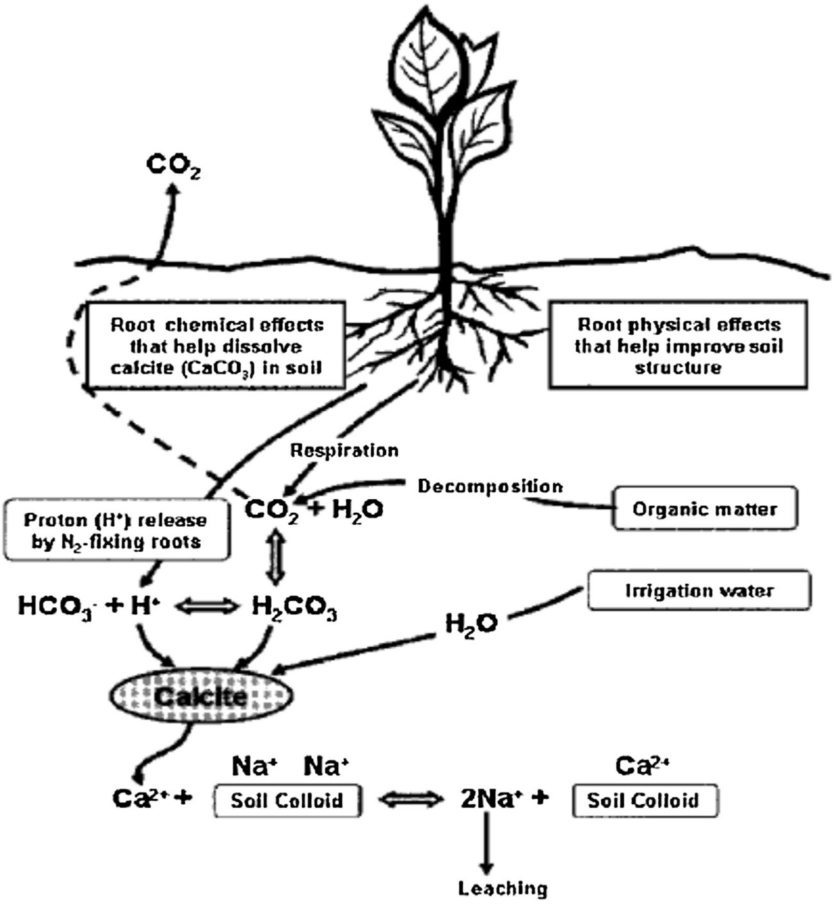

Fig. 8 – The process of soil reclamation by vegetative bioremediation (after Ozturk et al., 2006).

One of the halophytes reported to be suitable for reclamation of saline soils is *Suaeda salsa*, which can uptake the salt from soil and store it in plant tissue (Panta et al., 2014). The measured salt content in the shoot and root of *S. salsa* has been reported to be as high as 23–27% and 10–12% of dry weight, respectively (Zhao, 1991). In an attempt to extract additional nutrients from the soil along the west coast of South Africa, de Villiers et al. (1995) studied a biannual salt tolerant herb, *Mesembryanthemum barklyi*. Due to its ability to retain the salts in its plant tissue, they found it a highly successful biological solution for soil reclamation in the region. Another salinity-tolerant species for soil reclamation is *Kallar* grass (*Leptochloa fusca*) which can grow in saline sodic soils, enhances salt leaching and improves the physical condition for the subsequent establishment of other species. It can also provide biomass for use as forage (Akhter et al., 2004).

In an attempt to identify suitable plant species for remediation of salt-affected soils in arid and semi-arid regions, Rabhi et al. (2009) studied the desalinization potential of certain halophytes. They compared three plant species, namely *Sesuvium portulacastrum Arthrocnemum indicum* and *Suaeda fruticosa* under a deficit irrigation scenario. They found that these species absorb sodium ions through their roots and conduct them to their shoots where osmotic adjustment occurs. The high level of water content in the aerial organs of these species confirmed the osmotic adjustment mechanism. A total of 30 samples of each species were planted in six 8 kg pots. The pots were irrigated to half the field capacity of the soil. Also six additional pots without plants were used as control treatments. The aerial organs of the plants were cut, dried and weighed for further analysis after 170 days. They found that all of the studied species absorbed a large amount of sodium within the experiment period of 170 days, indicating a significant potential for soil salinity reduction. Fig. 9 demonstrates the variation of soluble sodium and EC in the experimental plots. Extracts of saline soil samples (1 g soil with 10 g distilled water) were taken from the upper 15 cm of the pots in which three halophytes [*A. indicum* (AR), *S. fruticosa* (SU), and *S. portulacastrum* (SE)] were grown over 170 days and constantly irrigated with tap water. IS and CS represent the initial and control soils (Rabhi et al., 2008).

Comparing the dry weight of the three species revealed that *Sesuvium portulacastrum* (SE) was the most productive halophyte as it had the maximum potential for sodium extraction from the root zones. Fig. 10 shows the percentages of extracted Na^+ compared with initial levels in the soil.

Zhao (1991) studied the potential of *Suaeda salsa* for desalinization of salty soils. He claimed that a density of 15 plants per m^2 will reduce the ratio of sodium ions in the upper 10 cm layer of the soil by 2.4%. If the number of plants is doubled in the same area, this value will rise to 3.8%. However the maximum reduction of the sodium ions was reported at a depth of 20–30 cm. The role of two halophyte species, *Juncus rigidus* and *Juncus acutus*, in decreasing the soil salinity of arid lands of Egypt was reported by Zahran and Abdel Wahid (1982). They found that *Juncus rigidus* reduced the soil EC from 33 to 22 dS/m in its growth cycle.

Several studies have been conducted in India on the application of fast growing halophytes for bio-reclamation of salty soils. Ravindran et al. (2007) examined the performance of five fast growing herb species, namely *Suaeda maritima*' *Sesuvium portulacastrum*' *Clerodendron inerme*, *Ipomoea pes-caprae*,

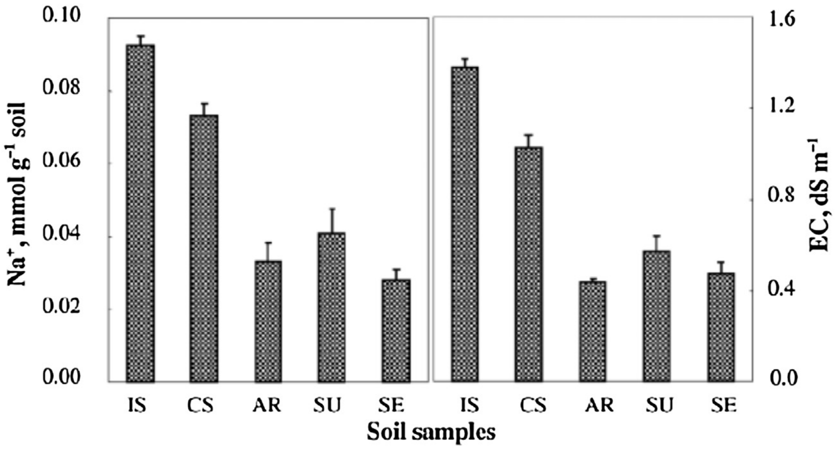

Fig. 9 – Soluble sodium content and electrical conductivity (EC) in soil solution (after Rabhi et al., 2008).

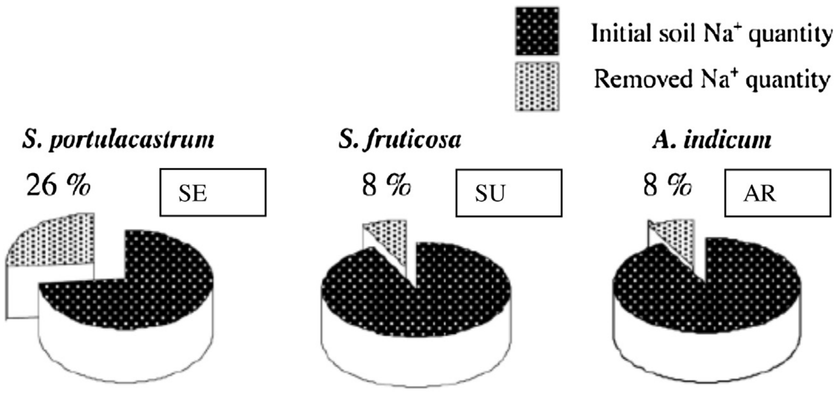

Fig. 10 – A comparison between desalination capacities in three halophytes (after Rabhi et al., 2008).

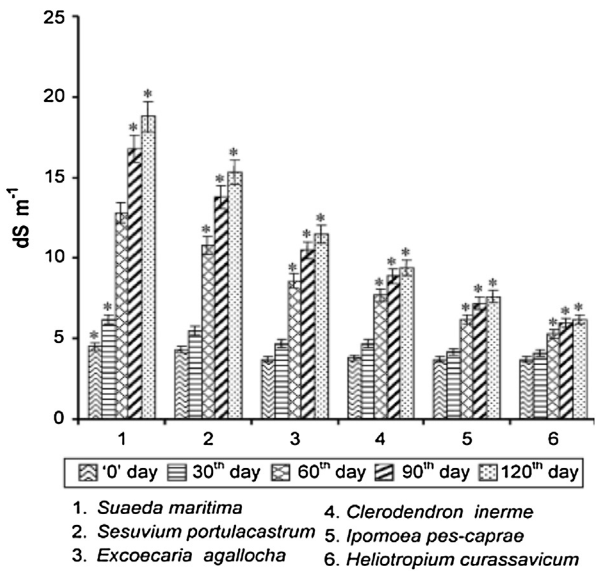

Fig. 11 – EC changes in six halophytes cultivated in natural saline soils (after Ravindran et al., 2007).

Heliotropium curassavicum and the tree, *Excoecaria agallocha*. The aerial organs of the plants were cut, dried and analyzed after 120 days. *Suaeda maritime* and *Sesuvium portulacastrum* recorded the highest amounts of salt accumulation in their tissues, and therefore had best performance in terms of desalination. The rate of EC changes in the different species over time are shown in Fig. 11.

The role of *Sesuvium portulacastrum* and *Suaeda fruticosa* on salt removal from soil was also studied by Messedi et al. (2004) and Sleimi and Abdelly (2002). The increase of soil salinity also is aggravated by overuse of ground water for agriculture as in the case of Rajasthan (India). Shekhawat et al. (2006) studied the possibility of soil reclamation using three plant species; *Salsola baryosma*, *Haloxylon recurvum*, and *Suaeda nudiflora*. The plants were sown in 14 field plots of area 13.5 m^2 and irrigated by a class of water known as C4-S4, having very high levels of pH, SAR and EC. According to Batayneh et al. (2012) water of C4-S4 class (i.e. very high salinity hazard-very high sodium hazard) is usually not suitable for irrigation of any type of soil. Soil samples were collected after 3 months from five different depths, namely 0–10, 10–20, 20–30, 30–40 and 40–50 cm. The fresh and dry weights of the aerial shoots were then measured. The results show the moderation of soil pH by the halophytes (Table 2).

Significant reductions of soil pH in the all of the experimental depth levels in the *S. baryosma* and *H. recurvum* plots were recorded. However soil pH in the 10–20 and 20–30 cm levels were increased in the *S. nudiflora* plots. In terms of EC reduction, *H. recurvum* and *S. nudiflora* were superior to *S. baryosma*.

Al-Nasir (2009) studied the effects of the three types of halophyte species (*Tamarix aphylla*, *Atriplex numularia*, *Atreplix hallimus*) on salt removal in saline-sodic soils in the Jordan Valley. They found that the maximum reduction in soil salinity occurred zones of high root density. Also the yield of salt-sensitive plants decreased at even low levels of salinity. But for salt-tolerant crops there was a higher threshold of salinity, below which yields did not decrease.

Recent studies have claimed that halophytes not only tolerate salts but also tolerate other stresses from heavy metals and possibly accumulated metals (Manousaki and

Table 2 – Effect of halophyte plantation on physical and chemical characteristics of soil (after Shekhawat et al., 2006).

Determination	Depth	*S. baryosma* plots		*S. nudiffora* plots		*H.recturvum* plots		Control plots	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
pH	0–10	8.16 a	8.13 a	8.13 a	8.04 b	8.44 a	7.73 c	8.10 a	8.42 b
	10–20	8.29 a	8.03 b	7.99 a	8.04 a	8.27 a	7.96 c	8.08 a	8.33 b
	20–30	8.48 a	7.88 c	7.97 a	8.02 a	8.27 a	8.01 c	7.90 a	8.16 b
	30–40	8.32 a	7.90 c	7.99 a	7.97 a	8.38 a	7.95c	7.95 a	7.96 b
	40–50	8.27 a	7.65 c	7.93 a	7.98 b	8.01 a	7.88 c	7.88 a	7.98 b
EC (1:2.5) ($\mu s\,cm^{-1}$)	0–10	768 a	967 b	930 a	199 c	1155 a	314 c	868 a	852 b
	10–20	1068 a	697 c	1142 a	167 c	1880 a	273 c	665 a	710 b
	20–30	1002 a	707 c	1092 a	167 c	1006 a	228 c	448 a	639 b
	30–40	971 a	754 c	949 a	175 c	939 a	246 c	421 a	629 b
	40–50	858 a	1200 b	585 a	233 c	648 a	279 c	421 a	581 b
Na^{+} ($mg\,100\,g^{-1}$)	0–10	33.75 a	97.25 c	84.75 a	47.75 b	74.25 a	33.75c	64.50 a	104.25 b
	10–20	64.50 a	90.75 b	45.00 a	63.75 b	80.00 a	37.75 b	74.50 a	98.25 b
	20–30	69.75 a	89.25 b	75.25 a	76.25 a	81.25 a	35.00 b	79.00 a	98.25 b
	30–40	73.50 a	96.25 b	78.50 a	81.25 a	77.23 a	39.00 c	80.00 a	92.00 b
	40–50	66.00 a	106.5 b	70.25 a	92.25 b	64.00 a	42.75 b	63.50 a	99.25 b
Ca^{2+} ($mg\,100\,g^{-1}$)	0–10	12.00 a	17.00 c	7.75 a	22.50 b	5.50 a	15.75c	19.50 a	11.50 b
	10–20	13.25 a	6.50 b	11.00 a	19.50 b	8.50 a	19.00 b	16.50 a	10.50 b
	20–30	14.25 a	8.00 b	9.75 a	18.00 a	10.25 a	14.50 b	11.75 a	9.75 b
	30–40	15.75 a	7.00 b	13.00 a	19.00 a	12.00 a	10.50 c	12.75 a	8.75 b
	40–50	14.00 a	12.00 b	11.00 a	18.00 b	11.75 a	13.50 b	13.25 a	10.00 b
ESP	0–10	50.58	77.95	81.8	55.31	80.79	46.01	62.3	79.0
	10–20	70.35	87.18	75.8	64.57	79.47	44.63	60.5	80.6
	20–30	73.09	84.59	74.5	70.84	77.99	46.44	66.1	80.09
	30–40	73.86	86.30	75.5	70.35	74.79	51.73	76.6	80.20
	40–50	72.70	82.64	63.5	74.13	71.56	50.61	66.1	76.07

Fig. 12 – Garden Lavender (*Lavandula intermedia*) (by John Bebbington FRPS).

Kalogerakis, 2010). Manousaki and Kalogerakis (2011) recommended halophytes as ideal candidates for phytoextraction or phytostabilization of heavy metal pollutants as well as for desalination.

5.2. *Mechanisms of desalinization by halophytes*

Halophytes adopt different functional approaches to reduce the salinity of the soil. These are grouped into two main classes of accumulating ions and excreting ions (Belkheiri and Mulas, 2013; Hagemeyer and Waisel, 1988). The ion accumulators (hyper-accumulators) store the excess sodium in their aerial tissues. Garden Lavender (*Lavandula intermedia*) is

Fig. 13 – *Leptochloa fusca* (http://plants.jstor.org/visual/presld0000707).

a xerophytic plant with long and thin leaves which are rolled downwards in the margins resulting in a small surface area to reduce evaporation (Fig. 12).

The function of excreting ions involves different mechanisms for desalinization. The most popular species in arid lands are *Zygophyllum coccineum*, *Aeluropus lagopoides*, *Cressa cretica*, *Limonium axillare* and *Zygophyllum simplex*. Due to the wide range of salinity and sodicity of soils, selection of the appropriate species is challenging. As an example *Kallar* grass [*Leptochloa fusca*], also known as Australian grass (Fig. 13) is a perennial forage growing in salt-affected soils (Malik et al., 1986). Many researchers refer to it as an appropriate salt-tolerant species for desalinization (Kumar and Abrol, 1984; Qadir et al., 1996; Sandhu and Qureshi, 1986).

The halophytes implement several types of strategies such as excluding, conducting, transferring, and accumulating to survive in the salt-affected soils (Fig. 14). The excluders pre-

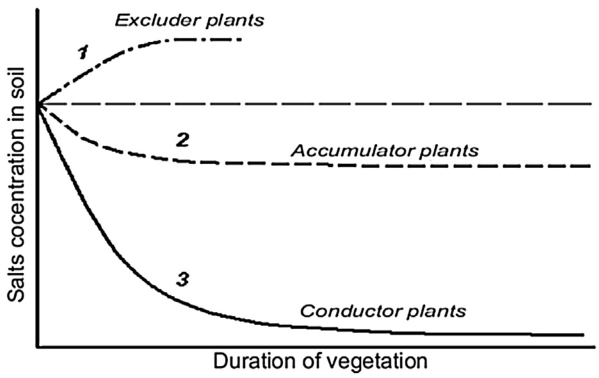

Fig. 14 – Effect on salt accumulation in soil for three categories of salt resistant plants (after Yensen and Biel, 2006).

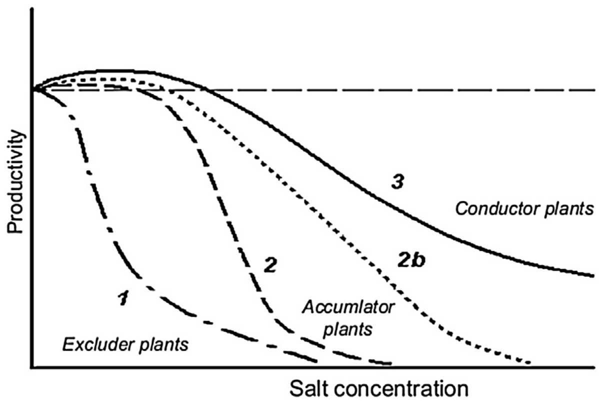

Fig. 15 – Production comparison between three types of halophytes (after Yensen and Biel, 2006).

vent the salt entrance to the roots. The conductors uptake the salt from soil and transfer it to the aerial organs and then disperse it away with the aid of wind (i.e. *Tamarix sp.* shown in Fig. 5). Typical salt conductors are termed as *crinohalophytes*. The accumulators extract salts and store it in the vacuoles of the plant cells in the root and shoot tissues (Jithesh et al., 2006; Yensen and Biel, 2006).

The productivity of these groups of plants is compared in Fig. 15. Whereas the salt excluder species cannot live in regions of high salinity, the other two groups show survival potential. Some of the salt accumulator plants (2b) may accumulate up to 50% of their dry weight as salts and yet have a similar high productivity to the salt conductor plants (3) under similar conditions.

Harvesting the aerial organs to remove the salt away from the polluted site is often not economic and harvested plant organs frequently contain such a high content of salt (between 25–54% of dry weight) that they might be inedible (Ajmal Khan and Weber, 2006). Hence, conductors may be preferable to accumulators.

6. Challenges of green remediation

Green remediation is a solar driven in-situ approach with relatively low costs. Also it does not generate secondary wastes and is usually accepted publically (Tahir et al., 2015). However, green remediation might require considerable time to be established and fully operational compared to engineering-based remediation (Kopittke and Menzies, 2005). The potential of toxic plants entering the food market through animal feeding or the fuel market as polluted woody tissues are other concerns. The depth of contamination is another issue. An appropriate root depth is often needed to reach the contaminants. In cases of limited root depth, planting in boreholes or pumping the polluted water to a shallower depth might be suitable alternative approaches. Contaminant heterogeneity is another issue that arises due to the spatial and temporal variability of pollutants. This often necessitates a precise remediation management strategy involving a combination of different methods (Chappell, 1997; Henry, 2000; Pilon-Smits, 2005).

7. Conclusion

Application of green remediation to control soil salinity is a very promising approach due to modern approaches in engineering-based remediation. Green remediation 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 and heavy metals. Selection of appropriate species according to the eco-physiological conditions of the environment as well as the methodology of cultivation helps this approach to be more efficient and economic. Plants 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 application of halophytes for phyto- and bioremediation and their effects on contaminated soils and waters. Such investigations will enhance the strategies of soil remediation by combining physical, chemical and biological systems.

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