Published Online on 21 November 2016

Proc Indian Natn Sci Acad **83** No. 1 March 2017 pp. 51-66

DOI: 10.16943/ptinsa/2016/48857

Review Article

Plants in Remediating Salinity-affected Agricultural Landscapes

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(Received on 05 May 2016; Accepted on 02 August 2016)

Soil salinity is a widespread problem throughout the world. Salinization makes productive land unproductive. This problem can be addressed by non-plant based, environment-friendly (*e.g.*, leaching of salts, chemical amelioration of soils, structural engineering modifications) and plant-based remediation (*e.g.*, phytoremediation). Non-plant based remediation provides rapid outcomes. However, they have several inherent problems, *viz.*, they are energy and cost intensive, need to be site specific, and are usually unsuitable in managing vast landscapes. In contrast, plant-based remediation, *viz*., phytoremediation, is a slower process, but is economical and environment-friendly. Phytoremediation is applied in areas that not only suffer salinity, but also in areas that include heavy-metal leachates such as mine areas and in landscapes that suffer sodicity. Further to improving soils by bringing them to near-natural conditions, phytoremediation, a worthwhile environment-friendly effort, provides many additional benefits such as improving nutrient availability in the restored soil. Keeping these in view, this article attempts to provide a comprehensive overview of salinity and its effect on plants, salinity-tolerance mechanisms in selected plants,various plant-based salinity remediation and management practices, such as phytoextraction, phytostabilization, phytotransformation, phytovolatilization, and rhizodegradation, and their contextual relevance. This overview while comprehensively summarizing the scientific bases in the historical and current developments in managing salinity-afflicted landscapes, should equip interested people in recruiting environmentally friendly management of salt-affected agricultural landscapes especially in developing nations.

Keywords: Environmentally Friendly; Organic Osmolytes; Restoration; Salt Ions; Sequestration; Stress Physiology

Introduction

Salinization, erosion, loss of nutrients and organic matter, acidification, compaction, and water logging are some of the principal causes for degradation of the agricultural landscapes. These processes damage *c.*12 million ha of land every year throughout the world (Lal *et al.*, 1998). Compounding this issue further, every year 2 million ha of world's agricultural land deteriorates only because of salinity, leading to either reduced or no productivity (Ashraf and Foolad, 2007). A majority of such degrading events is due to human activities driven by economic reasons. Intensified-farming practices have led to saline agricultural landscapes (McNeill and Winiwarter, 2004). For instance, injudicious irrigation accelerates mobilization and accumulation of salts in top soil resulting in irrigation-induced soil salinity (Yaalon, 2007). In Australia, clearing of extensively rooted native perennials to accommodate short-rooted exotic pasture crops (Johnson *et al*., 2009) is one primary cause in the increase of dryland salinity.

As per the present records (Rengasamy, 2006; Munns and Tester, 2008) a little more than 800 million ha of land in more than 100 countries of the world is salt-affected (Table 1). Even though saline soils are expected to occur only in soils in arid and semi-arid climate landscapes, they occur in subhumid and humid landscapes as well (Fageria *et al*., 2011). For instance, in the Canadian prairies close to 4.5 m ha of dryland cropping area suffers from salinization (Wiebe *et al.*, 2005). The United Nations Environment Program estimates that 50% of cropland and 20% of agricultural

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Table 1: Global distribution of saline and sodic soils

Land mass	Area (million hectares)		
	Saline	Sodic	Total
North America	6.2	9.6	15.8
Central America	2.0	—	2.0
South America	69.4	59.6	129.0
Africa	53.5	27.0	80.5
South Asia	83.3	1.8	85.1
North and Central Asia	91.6	120.1	211.7
Southeast Asia	20.0	—	20.0
Europe	7.8	22.9	30.7
Australasia	17.4	340.0	357.4
Total	**351.5**	**581.0**	**932.2**

Source: Rengasamy (2006)

land worldwide is salt-afflicted. It has been predicted that damaging global effects of increased salinization of arable lands could result in 30% loss of productive land in the next 15 years and up to 50% by 2050 (Wang *et al*., 2003). In addition, currently almost 4 million km^2 area is affected by sodicity, a soil condition where Na^+ represents >15% of the exchangeable sodium percentage (ESP) following the U. S. scientific convention.

Salinization occurs usually as a result of the combination of landscape, climatic factors and, human activities (Rengasamy, 2010). Further, the continuous rise of sea level in a warming world and natural calamities, such as tsunamis threaten greater salinity affliction through inundation of coastal areas. At least three types of salinity are recognized: groundwater-associated (dryland) salinity, non-groundwater-associated (transient) salinity, and irrigation-induced salinity. Salts diffuse from different sources, such as weathering of rocks that allows salt to be released over time (Podmore, 2009). Human-related sources include salts in poor-quality irrigation waters, animal wastes (manures and wash waters), residual salts from amendments of soil and water (addition of gypsum, sulphur, various acids), sewage sludge and effluents, and chemical fertilizers (Pitman and Läuchli, 2002). Loss of water through evapo-transpiration resulting precipitations of salts in soil solution (Pitman and Läuchli, 2002), decaying organic matter, connate or fossil salts naturally present in soils (Podmore, 2009), sea-water intrusion into streams and estuaries enabled by tidal events (Pitman and Läuchli, 2002), rainwater (Rengasamy, 2006), and salts associated with silty clay deposits derived from wind-blown sources (Bierwirth and Brodie, 2006) are some of the key causes.

Against such a context, we provide notes on how an environmentally friendly management of a seriously debilitating, agriculturally important land management issue can be addressed using plants. Before we evaluate the efficacy of this method, we explain how salinity bears an effect on plants: on their growth and photosynthesis, and how some of the plants have developed specialized physiological mechanisms to tolerate excess salt and how they respond to hypersalinity. Then we illustrate different tested and verified methods of salt management using plants. Since various abiotic factors influence plant-based salinity management, we explain them briefly with suitable examples in the succeeding section, which is followed by the selection of suitable plants. We conclude with a disinterested analysis of the strengths and weaknesses of phytoremediation and how this could be applied for the best outcomes.

Effects of Salinity on Plants

On Growth

Salinity affects plant growth (Munns and Tester, 2008), since the salt in the soil solution decelerates the ability of plant to take up water from soil solution, thus resulting in plants suffering water deficit and osmotic stress. When excess quantities of salt enter the transpiration stream, they affect transpiration, which, in turn, negatively affects growth inflicting a salt-specific, ion-excess effect (Shabala and Munns, 2012). Salt-affected plants usually bear stunted leaves, stems, and smaller fruits than usual. One of the extensively used fodder plants, *viz.*, *Paspalum vaginatum* (Poaceae), for example, shows a reduction of 40% in its shoot dry mass when grown in salinity (Uddin *et al*., 2012). In some instances, plant tissues thicken and become succulent, as shown in *Gossypium hirsutum* plants (Malvaceae) under salinity (Longstreth and Nobel, 1979). A direct relationship between increasing salt concentrations and diminishing growth rate in plants usually occurs. However, some of the established halophytes such as those of the Chenopidioideae (Amaranthaceae) maintain a better growth performance than the salt-tolerating glycophytes by adjusting ion toxicity and osmotic stress (Hasanuzzaman *et al*., 2014). Usually, the levels of salinity which the Chenopidioideae, Salicornioideae, and Salsoloideae (Amaranthaceae) can tolerate, the glycophytes cannot (Flowers *et al*., 2010). Because these halophytes are salt includers, they store greater levels of Na^+ and Cl^- in their cell vacuoles, and they are strongly capable of simultaneously synthesizing greater levels of organic osmolytes in cytosol for achieving better osmotic balance than what the glycophytes can achieve (Garthwaite *et al*., 2005; Flowers and Colmer, 2008). Usually growth of shoots is more intensely affected than that of the roots under various levels of salinity (Munns, 1993).

On Photosynthesis

Among the many physiological changes caused by salinity to plants, alteration and damage to photosynthesis are the most significant, because they affect plant performance. Under salinity stress, leaf biochemistry changes due to lowering of internal CO_2 concentration, resulting in the down regulation of photosynthesis (Chaves *et al*., 2009) and low levels of intercellular CO_2 deactivating ribulose-1, 5-bisphosphate carboxylase/oxygenase (Rubisco) activity (Tavakkoli *et al*., 2011). When CO_2 concentration in the leaf intercellular spaces decreases with stomatal closure, the sucrose-phosphate synthase and nitrate reductase activities concurrently decline. Whereas, when CO_2 concentration increases, the activity of Rubisco, and sucrose-phosphate synthase and nitrate reductase are restored rapidly. Under salinity-induced stress, when Na^+ and Cl^- levels increase in leaf tissues, photosynthetic performance concurrently decreases (Munns *et al*., 2006). Na^+ ion leakage into the cytosol inactivates many steps of photosynthesis, including electron transport (Allakhverdiev *et al*., 1999). High Cl^- concentration results in chlorophyll degradation caused by the shrinkage of thylakoid membranes and stacking of granal membranes in the chloroplast (Durner, 2013). Such changes to the chloroplast due to hyperaccumulation of Na^+ and Cl^- affect the quantum yield of PSII. When salt ions cross the threshold and reach high levels, chlorophyll degenerates (Yang *et al*., 2011). Although salt stress reduces the chlorophyll content, the extent of degeneration resulting in the reduction depends on the level of salt tolerance. Chlorophyll content usually increases in salt-tolerant species, whereas it decreases in salt-sensitive species under salinity (Akram and Ashraf, 2011). Salinity stress affects the hydraulic function in plants, leading to reduced water contents in leaves (Gorai *et al*., 2010). Relative leaf-water content influences plant growth through stomatal operations maintaining the turgor pressure ensuring osmotic adjustment. The importance of osmotic adjustment lies in the maintenance of relative-water content for an efficient photosynthetic performance (Meinzer *et al*., 1990). For example, under salt stress, *G. hirsutum* showed reduced levels of relative-water content, efficiency of photosystem II (PSII), net CO_2 assimilation rate, and stomatal conductance (Shaheen and Shahbaz, 2012).

Salt Tolerance by Plants

Plant capacity to survive in saline environments and to sustain their performance would broadly be recognized as 'salinity tolerance' (Flowers, 2004). As explained earlier, the key stress-inducing factors in saline environments to plants are salt-induced water deficits resulting in osmotic stress and salt-ion induced toxicity. By adapting varied physiological mechanisms, such as ion compartmentation in cell vacuoles and synthesis of organic osmolytes (*e.g.*, proline, and glycine betaine) (Ashraf and Foolad, 2007) plants survive in saline environments. Halophytes complete their life cycles in salt-concentrated environments (mostly dominated by NaCl) of ~200 mM (Flowers and Colmer, 2008); glycophytes tolerate salts far less than the halophytes (Flowers *et al*., 2015).

Ion Compartmentation

Salt tolerance by compartmentation is a frequently encountered mechanism in several salt-tolerant plants (Javid *et al*., 2011). Because both halophytes and salt-tolerating non-halophytes store and thus exclude salts in their vacuoles, their otherwise normal metabolic processes remain unaffected (Munns and Tester, 2008). For example, *Salicornia europaea* (Amaranthaceae: Salicornioideae) accumulates salt ions in its vacuoles (Lv *et al*., 2012). Salt ions, *e.g.*, Na^+, and Cl^-, are usually partitioned in cells in such a way that their concentrations remain in cells at 10–30 mM (Munns and Tester, 2008). Maintenance of homeostasis during salt uptake is generally enabled by compartmentation of salt ions to enable survival and performance of plants stressed by salinity (Hasegawa, 2013). Salinity–tolerant plants have the capacity to accumulate salt in cell vacuoles, thus preventing salt build-up in cytosol (Tuteja, 2007). Glycophytes, and even halophytes, cannot tolerate 'high–very high' salt concentrations in their cytoplasm (Gupta and Huang, 2014). To achieve homeostasis during high levels of salinity and consequent toxicity, plants move salt from cytosol either by transporting salt ions to vacuoles or by accumulating in mature tissues, destined to be abscised (Zhu, 2003).

Organic Osmolytes

Osmolytes are endogenously synthesized and/or accumulated compounds, which can be either organic (*e.g.*, amino acids such as proline, glycine betaine) or inorganic (*e.g.*, K^+). These osmolytes function as osmoregulators enabling the maintenance of subcellular–fluid balance, particularly when cells remain under stress (Munns, 2002). Synthesis of osmolytes is a protective mechanism that enables plant performance under various abiotic stress situations, including salinity (Shabala and Cuin, 2006). Osmolytes contribute to osmotolerance in plants by preventing enzymes from denaturation, thus ensuring membrane integrity (Ashraf and Foolad, 2007). In addition, organic osmolytes protect cell organelles by scavenging the reactive-oxygen species — a stress signal (Zhu, 2001). Among the various known organic osmolytes, the amino acids proline and glycine-betaine increase greatly in plant cells under salinity (Munns, 2002). These amino acids function as osmolytes in salt-affected plants, although which of the two occurs specifically in particular circumstances is not clear. In *Triticum durum* (Poaceae) seedlings, proline contributes to 40% of osmotic adjustment in cytoplasmic compartments, while the contribution of glycine-betaine accounts for up to 15% (Carillo *et al*., 2008). *Cynodon dactylon,* a well-known salt-tolerant glycophyte, on the contrary, produces higher quantities of glycine betaine (90 mM) than proline (35 mM) at 400 mM NaCl concentration (Marcum and Murdoch, 1994). Proline is probably the most widely distributed osmolyte in plants (Szabados and Savouré, 2010), because of the absence of enzymes such as choline-mono-oxygenase and betaine-aldehyde-dehydrogenase, which mediate betaine biosynthesis (Holmström *et al*., 2000; Bhuiyan *et al*., 2016 a).

The osmolytes – organic molecules of low molecular weight – are highly soluble compounds and are usually nontoxic at high cellular concentrations. They contribute to osmotolerance in plants by preventing enzymes from denaturation, stabilizing membranes or macromolecules, and playing adaptive roles in mediating osmotic adjustment (Ashraf and Foolad, 2007). When cell vacuoles accumulate Na^+ and Cl^-, there needs to be an adjustment of cytoplasmic osmotic potential by synthesizing of organic osmolytes and K^+ to match salt (especially NaCl) accumulation in vacuoles (Munns, 2002). When the vacuole cannot accumulate salt, then it accumulates in cytoplasm, denaturing and disrupting enzymatic functions.

Soil-salinity Remediation Tactics

Multiple strategies are currently used to manage soil salinity. These include plant based and non-plant based tactics. Each of these gains in relevance only when matched with local context – defined largely by various environmental factors and to some extent by economic feasibility – to achieve the best outcomes. Therefore, what could be appropriate in one landscape will not be so, in another. For instance, in landscapes where water is a limiting factor, leaching of salts, which requires substantive volumes of water, would be unsuitable. The area where the irrigation water is not available, sprinklers and drip or micro-jet irrigation are useful (Rains and Goyal, 2003). In many regions of Australia, where salinity outbreaks have already occurred, due to rising the shallow water table (Sadoddin *et al*., 2003), drainage and plant-based remediation are found as the most viable options in treating saline soils and restoring them to near natural conditions (Hajkowicz and Young, 2005).

Non-plant Based Remediation

The non-plant based remediation would include (1) leaching of salts, (2) manipulating water, (3) structural engineering options, and (4) applying chemical amendments. For details on these non-plant based remediation mechanisms, please refer to Rains and Goyal (2003), Suarez (1992), Barrett-Lennard *et al*. (2005), and Cramer (1992). In the context of chemical amendments, the use of high quantities of Ca^{2+}may be toxic to plants (Rengasamy, 2010) and gypsum (especially in calcareous saline-sodic soils) decreases the availability of micronutrients, such as Cu, Zn, Fe, and Mn (Mahmood *et al*. 2001). Supplementing N_2

material to low-salinity afflicted soils increases dry-matter production compared with non-saline treatments (Elgharably *et al*., 2010). However, at high salinity levels, supplementing N_2 material does not favour plant performance, since high N_2 bears an impact on the osmotic pressure of soil solution. The constraints of this practice are (1) low quality amendment materials include large fractions of impurities, and (2) high cost of chemicals. Although the above tactics are useful in some manner or other, the general findings both scientifically tested and those obtained from farmers is that plant-based restoration tactic is effective in multiple ways, including cost efficiency (Mishra *et al*., 2002; Qadir *et al*., 2002; 2007).

Plant-based Remediation

Phytoremediation

Phytoremediation is a tactic that recruits plants to reduce salts (*e.g.*, Na^+Cl^-, K^+Cl^-, $Ca^{2+}CO_3^{2-}$, $Mg^{2+}Cl^-$, $Na^+SO_4^{2-}$) from soil by accumulating them in their tissues (Kömives and Gullner, 2000; US–EPA, 2000). In this practice either the deliberately introduced plants into the salt-affected landscapes or those already existing in salt-affected landscapes perform by mobilizing and storing salts in them. In addition, their roots help in extracting the salts from the landscape.This tactic is referred in literature variously: phytoreclamation, biological reclamation (Qadir *et al*., 2007), biodesalination (Graifenberg *et al*., 2003), and soil desalinization using halophytes (Rabhi *et al*., 2009).

The ultimate purposes of any soil remediation process are to either absorb the contaminant materials or lower their concentrations to harmless (therefore, low) thresholds and to re–establish the physical, chemical, and biological characters of the affected soil and enable it to sustain the natural, innate fertility (Amer *et al*., 2013). In such a context, phytoremediation is an appropriate tactic, since it improves the physico-chemical and biological properties of affected soils (Arienzo, 2004). Also that, once a plant establishes in the nominated areas, it helps reducing the mobility and dispersion of contaminating materials through water and air. Phytoremediation is an emerging tactic to cleanse and/or stabilize large areas of affected landscapes (Garbisu and Alkorta, 2001). The preceding trials, using plants, were made on stabilizing pesticides (Sicilano and Germida, 1998), polyaromatic hydrocarbons (PAHs) and aliphatic petroleum-hydrocarbon soil contaminants (Hutchinson *et al*., 2003), and heavy metals (Adams *et al*., 2013a, b). Of late, phytoremediation tactics are employed in managing and restoring salt-affected soils (Qadir *et al*., 2007; Wu, 2009) and the generic strengths of useful plants lie in their ability to accumulate various metallic ions of salts. Illustrative datasets are supplied here (Tables 2, 3, 4, 5) from our work done in 2014–2016 using plants on remediating salinity–afflicted soilscapes in central-western New South Wales.

Phytoextraction – phytoaccumulation

In this process plants are used to extract contaminants and store them in their harvestable parts. This is the most widely practiced tactic to remediate saline soils (US–EPA, 2000). Halophytes and salt-tolerating non-halophytes, which have the capacity to store high concentrations of salts especially Na^+ and Cl^- in their shoots are ideal candidates in restoring salinity-afflicted landscapes (Manousaki and Kalogerakis, 2011). For example, salt tolerating *C. dactylon*

Table 2: Bioaccumulation factors of Ca, K, Mg, and Na in *Cyanodon dactylon* and *Thinopyrum ponticum* that occur naturally in two high-saline sites in central-western New South Wales, Australia

Poaceae	*Gumble* (Site 1)				*Cundumbul* (Site 2)			
	Ca	K	Mg	Na	Ca	K	Mg	Na
C. dactylon	4.33±0.7[a]	52.76±5.3	4.12±0.5	1.90±0.3	1.60±0.2	16.05±1.1	0.58±0.1	0.62±0.1
T. ponticum	2.06±0.4	39.93±5.0	3.57±0.6	7.32±1.8	0.43±0.1	13.75±2.5	0.19±0.0	1.26±0.2
P value	**	NS[b]	NS	**	NS	NS	*	NS

*,**Significant at P <0:05 and P <0:01, respectively.
[a]Mean± standard error; [b]Not significant.
(Source: Bhuyian *et al*., 2015a)

Table 3: Translocation factor of Ca, K, Mg, and Na in the naturally occurring grasses, *Cynodon dactylon* and in *Thinopyrum ponticum* measured in two high-saline in central-western New South Wales, Australia

Poaceae	*Gumble* (Site 1)				*Cundumbul* (Site 2)			
	Ca	K	Mg	Na	Ca	K	Mg	Na
C. dactylon	1.83±0.1[a]	1.80±0.1	1.28±0.0	1.23±0.3	1.51±0.1	1.75±0.1	1.77±0.2	1.21±0.2
T. ponticum	0.74±0.1	2.92±0.4	0.97±0.1	2.62±0.4	0.91±0.1	2.22±0.2	0.62±0.1	1.25±0.1
P value	**	**	**	**	**	*	**	NS[b]

*, **Significant at P <0:05 and P <0:01, respectively.
[a]Mean± standard error; [b]Not significant.
(Source: Bhuyian *et al*., 2015b)

Table 4: Bioaccumulation factors (BF) of two glycophyte taxa (*Melilotus siculus* (MS) and *Thinopyrum ponticum* (TP2)) and a halophyte taxon (*Tecticornia pergranulata* (TP1)) in simulated salinity trials

Salinity (dSm^{-1})	BF Na^+			BF Cl^-		
	MS	TP1	TP2	MS	TP1	TP2
0.0	22.1±1.9[a]	441.1±19.3[b]	18.4±14.7[a]	486.1±373.2[a]	1830.9±356.9[b]	214.3±184.0[a]
2.5	47.8±1.0[a]	223.5±150.2[ab]	17.2±9.6[a]	117.6±30.6[a]	429.1±362.6[a]	147.3±20.3[a]
5.0	4.3±0.4[a]	157.4±73.5[ab]	9.4±2.5[a]	45.0±33.4[a]	300.4±95.9[a]	34.0±17.7[a]

Mean±SD, *SD*, standard deviation.
Different letters indicate significant difference between species at Bonferroni at 5% level.
(Source: Bhuyian *et al*., 2016b)

Table 5: Translocation factors (TF) of two glycophyte taxa (*Melilotus siculus* (MS) and *Thinopyrum ponticum* (TP2)) and a halophyte taxon (*Tecticornia pergranulata* (TP1)) in simulated salinity trials

Salinity (dSm^{-1})	TF Na^+			TF Cl^-		
	MS	TP1	TP2	MS	TP1	TP2
0.0	1.8±0.3[a]	18.1±2.1[c]	1.0±0.5[a]	3.0±0.4[a]	20.2±1.9[bc]	1.7±0.7[a]
2.5	11.9±3.5[bc]	7.7±2.5[ab]	0.8±0.1[a]	24.6±3.3[c]	2.8±4.4[abc]	1.8±0.0[a]
5.0	7.1±1.5[bc]	6.8±0.2[ab]	0.8±0.3[a]	9.2±5.1[ab]	11.9±1.0[abc]	1.7±0.5[a]

Mean±SD, SD, standard deviation.
Different letters indicate significant difference between species at Bonferroni at 5% level.
(Source: Bhuyian *et al*., 2016b)

accumulates Na^+ and Cl^- in glands in their leaves (Marcum and Murdoch, 1994; Parthasarathy *et al*., 2015) and *T. pergranulata* accumulate salts in cell vacuoles (Flowers and Colmer, 2008). If harvesting is the strong possibility, then the less salt-tolerating, but salt-accumulating plants such as *Brassica juncea* (Brassicaceae) are indeed useful (Susarla *et al*., 2002).

Phytopumping and Water-balance Control

Phytopumping involves the use of plants as a hydraulic barrier to either create an upward movement of water in roots, thus preventing contaminants either percolating down or dispersing horizontally (Pilon-Smits, 2005). In this process, plants function as 'organic pumps' to draw large volumes of contaminated water enabled by transpiration (Susarla *et al*., 2002). Different species of *Salix* (Salicaceae) use up to 200 L of water day^{-1} (Gatliff, 1994) and deep-rooted perennial forage plants, such as *Medicago sativa* (Fabaceae) use large volumes of soil moisture thus preventing excess water from moving into the water table (Ridley *et al*., 2001). Such plants are potential candidates in such a management process.

Phytostabilization

Phytostabilization involves two steps: (1) immobilization of salts (Gaskin, 2008) and (2) accumulation of salt ions in roots rather than shoots (Huang and Chen, 2005). Plants chosen for use in phytostabilization tolerate salt, but do not translocate it to their aerial parts, as in *Populus alba* (Salicaceae), which accumulates 90% of Na^+ in their roots, whereas its concentration in shoots remain at low levels (Imada *et al*., 2009). Accumulation of the bulk of absorbed salts in roots indicates that this is an efficient salt-management mechanism (Tester and Davenport, 2003). Here plant roots play a key role by modifying the pH and soil-moisture content around roots, thus coagulating the salt ions and reducing their ready availability to other plants

Phytotransformation – phytodegradation

Phytotransformation–phytodegradation process involves absorption of salt ions that occur at high levels in the soil, movement into plant tissues, and breaking them down into either less toxic or non-toxic compounds *via* several metabolic steps (Singh and Jain, 2003). Plants synthesize a range of enzymes such as dehalogenase, peroxidase, nitroreductase, nitrilase, phosphatase, which enable the breakdown of toxic materials (Susarla *et al*., 2002;Gaskin, 2008). Of late, interest is growing in clarifying the role of symbiotic endophytic microorganisms in phytodegradation tactics (Zhuang *et al*., 2007). The endophytic fungi are particularly critical for the biosynthesis of gibberellins, which play key roles in mitigating abiotic stresses. Examining the role of the endophyte *Penicillium minioluteum* LHL09 (Eurotiales: Trichomaceae), Khan *et al*. (2011) explain that low endogenous abscisic acid and high salicylic acid accumulation elucidated the stress mitigation capacity of *P. minioluteum*. *Pencillium minioluteum* increased the daidzein and genistein contents in *Glycine max* (Fabaceae) under salt stress. Khan *et al*. conclude that *P. minioluteum* enabled *G. max* to mitigate adverse effects of salinity stress by influencing biosynthesis of hormones and flavonoids.

Factors Influencing Phytoremediation of Salt-affected Soils

Phytoremediation is influenced by an interaction among different environmental factors, such as soil type, pH, organic-matter content, temperature, and availability of water and oxygen. Some factors affect phytoremediation directly and others impact on it by altering the availability of salt ions in a usable form to plants (Gaskin, 2008). Overall several environmental and biological factors regulate the availability and absorption of excess salt ions in plant rhizosphere.

Soil Texture

Soils with higher clay content have greater water retention capacity than sandy soils and this, combined with slower drainage, leads to increased retention of salts, especially during periods of high soil evaporation (Seita *et al*., 2011). Those plants that are adapted to a particular soil type at salt-affected sites will be more successful for use in phytoremediation than those adapted to living in different textures. For example, *Sesbania bispinosa* (Fabaceae) is more suitable for the remediation of coarse textured, calcareous saline-sodic soil, and produces good quality forage, which also facilitates symbiotic N_2 fixation (Qadir *et al*., 1997). In contrast, *Leptochloa fusca* (Poaceae) is more suited to fine-textured, calcareous soils with higher levels of salinity and sodicity (Oster *et al*., 1999).

Soil-organic Matter

Soil-organic matter influences salinity remediation efforts. Adding organic matter (OM) to saline soils can decrease EC and ESP, and increase water-holding capacity, water infiltration, soil-bulk density, and thus aggregate stability (El-Shakweer *et al*., 1998). In addition, OM also influences microbial population build up (Paul and Clark, 1996). Microorganisms, acting similar to osmolytes, accumulate salts balancing their intracellular osmotic potential (Oren, 1999), thereby reducing environmental salinity. For example, Okeke *et al*. (2002) demonstrate that *Haloferax denitrificans* (Halobacteriales: Halobacteriaceae), *Paracoccus halodenitrificans* (Rhodobacterales: Rhodobacteraceae) and a species of *Citrobacter* (Enterobacteriales: Enterobacteriaceae) significantly reduced both perchlorates and nitrates in the experimental brine solution tested by them.

Soil pH

Soil alkalinity-acidity is a critical determinant of species distribution (Allen *et al*., 1997), because pH influences nutrient availability for plants. The availability of macronutrients such as, N_2, P, K, Ca, Mg, and S, decreases when pH is >6 (Larcher, 1980). Whereas, Al and Mn are readily available at pH <6, but reach toxic levels as pH drops further (Barbour *et al*., 1987). In alkaline soils (pH >8), Mn, Fe, and $P0_4$-s are fixed as relatively insoluble compounds and thus, become less available to plants (Larcher, 1980). Most bacteria operate optimally from neutral to near alkaline pH, while fungi occur abundantly under acidic conditions (Leahy and Colwell, 1990). Vascular plants have specific pH tolerance, but most of them perform optimally at pH range between 5.5 and 7.5 (Barbour *et al*., 1987). At pH levels <3 and >9, vascular plant protoplasts coagulate (Larcher, 1980) disabling plant performance.

Soil Temperature

Soil temperature influences phytoremediation (Frick, *et al*., 1999) and also the evaporation rate from soil and consequent salt accumulation. Temperature influences ion movement transmitting electrical charges. Under such circumstances, the carrier velocity (= the electrical conductivity, EC) of an aqueous solution remains directly proportional to temperature. The EC of water and temperature are linearly related in the 0–25ºC range, with a change in EC of around 1.8%/ºC (Hayley *et al*., 2009). Vascular plants react differently to temperature and various levels of salinity (Wright and Wellbourn, 2002). For instance, germination in *Phragmites australis* (Poaceae) increased by a combination of low mean temperature (10–25ºC) and midrange (15 ppt) of salinity (Greenwood and MacFarlane, 2006). *Cynodon dactylon* shows a wide amplitude of variation in growth to varying soil temperatures and salinity levels (Grattan *et al*., 2004; Wu *et al*., 2006).

Water and Oxygen Availability

Plant growth can be affected by waterlogging and high levels of Na^+ and Cl^-. It is common for groundwater induced salinization to occur in valley floors where waterlogging is also present. Waterlogging causes either hypoxia or anoxia in soils. However, in waterlogged conditions, phytoaccumulation of Na^+ and Cl^- increases in shoot tissues. Waterlogging in general can cause an average 228% increase in Na^+ concentrations and a 135% increase in Cl^- concentrations in shoot tissues (Barrett-Lennard, 1986; 2003). In some studies, the results are staggering. For example, a study testing the salt-accumulation capacity of *Eucalyptus camaldulensis* (Myrtaceae) showed that salt accumulation increased in shoots after *c*. 80 days of 'waterlogging+salinity' treatment showing 850% and 590% concentrations of Na^+ and Cl^-, respectively (van der Moezel *et al*., 1988). In contrast, Liu *et al*. (2008) have reported that phytoaccumulation of Na^+ and Cl^- increased in *Suaeda salsa* (Amaranthaceae: Chenopodioideae) with decreasing moisture levels in the saline soil tested.

Plant and Plant-associated Factors

Plant architecture, nature and quantity of root discharges, and mechanical effects of roots are some of the key plant factors that affect phytoremediation. Root architecture is one key factor in phytoremediation efforts. Plants such as those of Poaceae, bearing fibrous root systems, are more effective phytoremediators because they extend over a wider volume of soil than those annuals which bear taproots (Aprill and Sims, 1990). Plants with herringbone root morphology are more efficient than those with dichotomous morphology (Fitter *et al*., 1988). Poaceae could be effective agents in the remediation of shallow, transient salinity, but for remediation of deep groundwater-induced salinity tap-root plants could be more efficient (Robson, 2003).

Deep-rooted plants generally show a greater capacity to perform better in salinity affected landscapes than shallow-rooted plants (Brady and Weil, 1996), since the former category of plants can efficiently utilize water available at deeper locations, especially during periods of rainfall deficiency. Moreover, deep-rooted plants lower the ground water-table level and thus the salinity. In Australia, perennial deep-rooted plants, such as *Medicago sativa* (Fabaceae) lower water table and therefore salinity (Ridley *et al*., 2001). *Cynodon dactylon* (Poaceae) and *Melilotus siculus* (Fabaceae) (Hameed and Ashraf, 2008; Teakle *et al*., 2012) have relatively long and spreading root systems, and therefore have been identified as useful taxa in reducing the watertable height in saline soils. *Tecticornia pergranulata* tolerate both salinity and waterlogging, because of its robust adventitious root system (Rich *et al*., 2008). *Thinopyrum ponticum* (Poaceae) too have an extensive root system spreading to ~5 m in depth and is useful in lowering the water table in saline soils (Bleby *et al*. 1997). Roots also play another vital role in leaching Na^+ down to deeper soil layers in saline-sodic soils. In such soils, the inorganic carbon generally occurs as calcite ($CaCO_3$) and dolomite (Ca.Mg $(CO_3)_2$) (Wong *et al*., 2010). However, the minimal dissolution capacity of calcite and dolomite (several fold lesser than calcite) prevents the release of sufficient Ca^{2+} to replace the excess Na^+ in the soil (Qadir *et al*., 2007). When revegetating the salinity-affected areas, plants enhance the dissolution of inorganic carbon (*e.g.*, $CaCO_3$) by the release of CO_2 through root respiration, and this CO_2 dissolves with soil water and forms H_2CO_3. In addition, roots of legumes usually release protons (Mubarak and Nortcliff, 2010). H_2CO_3 and the proton (H^+) facilitate the dissolution of inorganic carbon, which release Ca^{2+} into the soil solution. The Ca^{2+} thus concentrated displaces exchangeable Na^+ from cation exchange complex sties and eventually Na^+ leaches down with water (Naidu and Rengasamy, 1993; Qadir *et al*., 2005).

Release of CO_2 by plants in soil have been quantified in some phytoremediation studies in both sodic and saline–sodic soils. For instance, Robbins (1986) quantified the root zone CO_2 of *Hordeum vulgare* and *Agropyron elongatum* (Poaceae), *M. sativa* (Fabaceae), and *G. hirsutum* (Malvaceae) during remediation of calcareous sodic soil and concluded that the two tested Poaceae produced considerable quantities of soil–atmospheric CO_2 that facilitated leaching of Na^+. Since different plant species produce different quantities of CO_2, plant species, which produce more CO_2 can be an effective candidate to enhance leaching of Na^+ (Qadir *et al*., 2007). In northern Egypt, after two years, both physical (*e.g.*, ponding) and chemical (*e.g.*, application of gypsum) treatments were less effective in reducing salinity than using native grasses such as *Phragmites communis* and *Panicum repens* (Poaceae) (Ghaly, 2002). Na^+ removal by leaching (due to root zone CO_2) is a more-effective mechanism than chemical restoration (*e.g.*, application of gypsum) (Qadir *et al*., 2005).

Plant Selection for Use in Phytoremediation

Selection of appropriate plants is one critical step in efficient phytoremediation (Frick *et al*., 1999). Species which can achieve normal growth in a saline landscape and accumulate high quantities of salt are the best candidates for use in phytoremediation of salt-affected landscapes (Nasser *et al*., 2013). Those which can produce greater biomass together with the capacity to tolerate salinity, sodicity and periodic inundation could serve as candidates of choice in remediating salt-affected areas (Qadir *et al*., 2007). Plants need to be selected with caution so that they provide a maximum root zone influence through the mechanical activity of roots, secretion of root exudates, and microbial interactions in the rhizosphere (Gaskin, 2008). A major constraint to successful application of phytoremediation practices in Australia has been with the availability and selection of appropriate plant species responding to the above (Gaskin, 2008). For right plant selection, a screening procedure helps immensely. An assessment of plants at naturally occurring field sites is step 1, after which the species that hold promise need to be trialled in controlled environments (Olson and Fletcher, 2000). Documentation of the phenology of plants that occur and grow naturally at saline sites, growing them in measured saline soils under greenhouse or growth chamber conditions, and subsequent field trialling under saline conditions are all necessary stages of evaluation (Robson, 2003). Using those plants that grow naturally in salt-affected areas is a cost-effective alternative as a land-management strategy. Because they already occur there, the extra cost and effort of sowing and establishing the plants is avoided. Some plants can colonize saline areas naturally. Examples of such plants include *P. australis* and *P. repens* (Poaceae), *Apocynum venetum* (Apocynaceae), and *Chenopodium album* (Amaranthaceae: Chenopodioideae), which have been found to be salt-tolerant and useful in restoration efforts (Hamidov *et al*., 2007). An assessment of the prevalent floristic composition of these salt-affected landscapes, taking the overall weaknesses and strengths into consideration is highly a useful tactic at planning stages (Chu, 2008). Phytoremediation is economical when the plants are useful as food and fuel for humans and fodder for animals. Twenty-six salt-resistant plant species, for instance, have been found to provide 30 products and services of value to agriculture (Barrett-Lennard, 2002). Local utilization is another critical issue that regulates the economic perspective of products.

Efficiency of Phytoremediation

In recent years, plant-based remediation of contaminated landscapes in general and salinity affected landscapes in particular, has emerged as an economical, environmentally-friendly, and aesthetically acceptable tactic (Dickinson *et al*., 2009). Although a few limitations of this practice prevail, the enormity of benefits makes this practice increasingly sought after.

Strengths

Low cost of this tactic is one key strength. Phytoremediation is an *in-situ*, solar-driven technique. Moreover, the costs towards planting, fertilization, tillage, and harvesting are far less compared with associated administrative costs including regulatory reporting, on-site management, and analysis of data (Gaskin, 2008). By and large, phytoremediation is at least 10-fold cheaper than structural engineering-based remediation methods, such as soil washing or burning, soil excavation or pump-and-treat systems (Glass, 1999). It exploits the inherent capacity of plants in remediating saline soils and water, inflicting minimal disturbance to other related systems (Dickinson *et al*., 2009). Use of *in-situ* plants avoids significant environmental impacts resulting from land disturbance associated with soil preparation for planting. Further, these disturbances may cause additional, downstream impacts, for example, the mobilization of salts into waterways.Plants used in this method also help stabilization of soil, reduction of soil erosion, and protect humans from the inhalation of fine-soil particles (Frick *et al*., 1999). This provides two key benefits to farmers who struggle with salinity in the farming landscapes: The necessity to procure chemical amendments such as gypsum is defeated. Overall benefits enhance both financially and at the farm during and after reclamation (Qadir *et al*., 2007). These methods provide additional benefits by increasing nutrient availability in the reclaimed soil over any other reclamation strategy. For example, after phytoremediation of saline–sodic soil, the levels of N, P, Fe, Mn, Cu, and Zn have been found to increase in the reclaimed soil (Malik *et al*., 1986; Qadir *et al*., 1997). In Australian alkaline–sodic soils, availability of N (from urea) became a problem because of low urease activity at >8 pH (Naidu and Rengasamy, 1993). However, the activity of urease and dehydrogenase increased in such areas after phytoremediation trials recruiting *Desmostachya bipinnata*, *Sporobolus diander*, *Diplachne fusca*, and *C. dactylon* (Poaceae) (Rao and Ghai, 1985). *Sesbania cannabina* also increased in urease and dehydrogenase activities after green manuring in sodic soil (Rao and Pathak, 1996). Other than these specific strengths, the general advantages of using plants would be that carbon sequestration will be improved (Qadir *et al*., 2007) and enable reduction of noise pollution from industrial sites.

Weaknesses

Phytoremediation is a relatively slower method than chemical-based restoration methods; usually several seasons are necessary for the site clean-up (McIntyre and Lewis, 1997). Therefore, it is a less preferred approach where the salt contamination requires rapid clean up (Susarla *et al*., 2002). Plants may not grow when salt levels are extremely high. Therefore, phytoremediation cannot proceed without pre-treating sites (Cunningham *et al*., 1996). Crop rotation may be an imperative prerequisite. Some phytoremediation approaches in the salt-affected areas have not been successful because salt-tolerant plant was not the first in crop-rotation practice (Muhammed *et al*., 1990). Success of plant-based remediation depends on root depth because roots need to access salts. However, not all plants have roots that can efficiently reach salts. A phytoremediation prescription found ideal in one landscape context need not be appropriate for every other landscape because site-specific conditions are generally variable (McIntyre and Lewis, 1997). Furthermore, plants as living organisms are vulnerable to attack by insects and pathogens (Susarla *et al*., 2002), which can affect plant-based remediation efforts. A further important challenge is the need for greater choice of agriculturally suitable and therefore economically viable salt tolerant species, permitting affected landholders to offset rehabilitation costs and generate an income from the restored land.

Conclusion

Affliction of landscapes, especially agricultural landscapes by salts necessitates sustainable management practices that would stretch far into the future. Chemical, engineering, and biological tactics are the principal options that are available to us today. However, each of these tactics has its own strengths and shortcomings. The definitive negative points of structural– and chemical–based efforts to restore salinity affected sites are enormous power usage and further environmental contamination in chemical–based strategies and lengthy clean–up time in phytoremediation–based strategies. Chemical approaches can further contribute to environmental problems, and engineering work often just shifts the problem elsewhere. Plant-based remediation gained in significance in recent times and it has, since then, moved on to receive attention with ongoing searches for new accumulator and hyperaccumulator species. This has enabled success in various types of salinity-afflicted sites across the world. Nevertheless, several arguments against the strengths of plant-based remediation tactics in restoring saline and hypersaline landscapes do occur. These arguments challenge the length of time required and often what should be done with the salt-including plant material. The tasks in front of plant-based remediation measures are substantial, but the strengths of phytoremediation salinity contexts — and the collateral ecosystem services they offer — outweigh the identified weaknesses. To date, the performance of plants tested and used in salinity affected sites for extraction of salts is well documented, although a consensus on several issues is yet to be reached and will require continuing investigations: a majority of the recognized plants accumulate salts in their rootsystems; we need to know more of the physiology of plants used in the extraction, volatilization and immobilization of salts, and we have not yet identified any strong salt hyperaccumulators except the established halophytes, especially those taxa belonging to the *Betoideae, Chenopodioideae, Salicornioideae, Salsoloideae*, and *Suaedoideae* (Amaranthaceae). Enormous potential exists; but we need to explore further to know more of the strengths and weaknesses of several salt-tolerant and economically useful plants and their deployment in the remediation of salt-affected landscapes.

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