Chapter 15
Phytoremediation of Saline Soils for Sustainable Agricultural Productivity

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Abstract Salinization of soils is one of the major factors which severely affect the agricultural productivity worldwide. Due to salinity, more than half a billion hectares of land are not being properly used for crop production. Thus, there is a need to search means to improve saline soils so that such soils could support highly productive and meaningful land-use systems to meet the current challenges of global food security. Although permanent solution of soil salinity problem necessitates a sound drainage system to manage the rising water table, this option, being energy- and cost-intensive cannot be employed on a large scale on vast areas. Phytoremediation or biological approach, i.e., plant-based strategies for improvement of deteriorated soils is an appropriate option. Phytoremediation of saline soils can be done by cultivating suitable plant species as well as by Exploiting the ability of plant roots to improve the dissolution and enhance levels of Ca in soil

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solution to efficiently remove Na from the soil cation exchange complex and leach it from the root zone. During the amelioration process, soil-aggregates stability, root proliferation, soil hydraulic properties and availability of nutrients to plants are also improved. Such improvement in soil properties facilitates cultivation of less tolerant plants, improves the environment in general, and the climatic conditions by enhancing carbon sequestration.

Keywords Salt removal · Salt tolerance · Plant productivity · Soil properties · Halophytes · Carbon sequestration

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1 Introduction

Salinization is one of the most intriguing and fundamental problems for agriculture particularly in the semi-arid and arid regions of the world (ICARDA 2002). It prevails in more than half of the irrigated areas (Cheraghi 2004) and is a major constraint for the agricultural productivity in Pakistan, where more than 6.3 million ha (Mha) of land is salt-affected (Khan et al. 1998). The contamination of soils due to salinization hampers the balance between the functions (goods and services) supplied by the natural resources (land and water) and the demands of societies which ultimately affects the livelihoods of the population of that area (Abdel-Dayem 2005). Salt-contaminated soils are increasing due to intensive cultivation with high input demanding crops (Akhter et al. 2003), lack of drainage system in the farmers fields in irrigated areas, as well as discharge of soap, leather and oil industries in irrigated water (Pitman and Läuchli 2002). It has also been observed that excess of salts reduce the permeability of soils (Ashraf 2007). Salt-affected soils usually contain a variety of inorganic salts with cations like Na^+, Ca^{2+}, Mg^{2+}, and K^+, and anions like Cl^-, $SO_4{}^{2-}$, $HCO_3{}^-$, $CO_3{}^{2-}$, and $NO_3{}^-$ (Tanji 2002) which adversely affect plant growth and productivity due to causing ion toxicity or osmotic effect on plants (Parida and Das 2005; Läuchli and Grattan 2007).

With the increase in world population, food, feed and industrial material resources are shrinking day by day. This urges the utilization of salinized wastelands for plant production. Different approaches for remediation of these lands are being used for the last few decades which include construction of drainage system, chemical amendments, tillage operations, crop-assisted interventions etc. (Oster et al. 1999). So, identification of remediation techniques for salt-contaminated soils which are environment friendly is necessary. Phytoremediation i.e., utilization of plants to remediate contaminated soils, is one of these techniques which is environmental friendly. The cultivation of salt tolerant plants having ability to absorb excessive salts from root zone and accumulate them in plant body is an effective low cost option. These plants not only remediate the salt-contaminated soils but also provide food, fodder, fuel wood and industrial raw material and increase the income of the farmers owning salt-affected lands.

Plants having ability to remove salts from contaminated soils have been identified by many workers (Ashraf et al. 2005a). Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan is playing a key role in disseminating these plants all over the world especially in under-developed and developing countries through different national and international projects. Most of the selected plants are introduced on salt-affected soils for cultivation. The field experiments related to this topic have been conducted at two Biosaline Research Stations (BSRS) of NIAB, one located at Rakh Dera Chal near Lahore (BSRS−I) at longitude 74° 7′ E and latitude 31° 6′ N and the other at Pakka Anna near Faisalabad (BSRS−II) at 73° 05′ E longitude and 31° 24′ N latitude where average annual rainfall is 500 mm. *Suaeda fruticosa*, *Atriplex lentiformis* and *Kochia indica* (Chenopodiaceae), and Kallar grass (*Leptochloa fusca*) and *Sporobolus arabicus* (Poaceae) were grown on both the stations using brackish groundwater for irrigation (Table 15.1). Soil samples (0–20, 40–60 and 80–100 cm depths) were collected before and after the cultivation of above mentioned plant species and analyzed for various physico–chemical properties (Table 15.2) using mostly the methods described by the US Salinity Laboratory Staff (1954).

Table 15.1 Characteristics of tube–well water at BSRS–I and II

	Values	
Characteristics	BSRS–I	BSRS–II
EC (dS m^{-1})	0.14	4.97
pH	7.6	8.2
TSS (mg L^{-1})	89.6	3878
SAR	7.8	40.5
SAR adj	19.8	101.25
RSC	9.7	21.60
Soluble ions (me L^{-1})		
Na^+	10.4	51.2
K^+	0.2	0.4
Ca^{2+}, Mg^{2+}	3.6	3.21
Cl^-	0.7	13.75
$CO_3{}^{2-}$	–	1.5
$HCO_3{}^-$	12.8	21.75
$SO_4{}^{2-}$	0.4	17.35

Table 15.2 Characteristics of soil of BSRS–I (Lahore), and II (Faisalabad)

	Range	
Soil characteristics	BSRS–I	BSRS–II
Soil texture	Sandy clay loam	Sandy loam
Clay (%)	18–23	12.5–15.5
Silt (%)	52–57	16.5–19.5
Sand (%)	23–25	65–71
EC (dS m^{-1})	1.25–2.22	12–27.24
pH	10.4–10.5	7.82–8.92
Bulk density (g cm^{-3})	–	1.38–1.58
$CaCO_3$ (%)	–	12–23
$CaSO_4.2H_2O$ (%)	0.065–0.189	2.56–4.15

2 Changes in Soil Physical Characteristics

Plants generally influence the physical properties of the soils like soil porosity, soil hydraulic permeability (Kfs), bulk density, soil water retention and soil structural stability (Marschner 1995). These properties can be improved by the cultivation of salt tolerant plants through their different activities.

Roots of plants are necessary to maintain the soil structure and cultivation of plants having lower depths are responsible in developing macropores in the soil profile, due to which soil porosity improves (Czarnes et al. 2000; Yunusa and Newton 2003). Roots are also responsible in removing the entrapped air from the soil pores (Tisdall 1991). They also facilitate the Na leaching and replace it with other cations from the deeper layers of the soil which is triggered by deep-rooted vegetation that can withstand different levels of salinity during phytoremediation. Akhter et al. (2004) has reported 15% increase in soil porosity by the cultivation of Kaller grass for five years on salt-affected soils. Similarly, Yunusa and Newton (2003) have reported that cultivation of salt tolerant plants improves the physico-chemical properties of soil and help remove subsoil salt contamination. Soil porosity is significantly enhanced by the rooting system of these plants. It has been proved that deep tillage is beneficial in ameliorating subsoils having low porosity, but these benefits are not permanent without vegetation cover (Cresswell and Kirkegaard 1995). Roots of some plant species have potential to act as tillage tools which is called biological drilling. It is proving as a promising alternative to deep tillage necessary to ameliorate the dense subsoils. Biological drilling has two stages: (a) creation of macropores in the subsoil by the penetration of roots in the compact soil layers followed by their decay resulting in an improvement of gaseous diffusion and water movement (b) benefits for the subsequent crop(s) after improvements in subsoil macroporosity (Cresswell and Kirkegaard 1995). Some plants like *Atriplex*, *Suaeda fruiticosa*, *Paspalum notatum* and *Festuca arundinacea* have ability to grow on compact soil layers due to their deep and strong root systems as a result of which soil porosity is improved. Field experimentation with *Atriplex* and *Suaeda* showed that their cultivation on salt-affected soils is beneficial because of their strong rooting system which penetrates into soils with low-permeability (Ashraf 2007). A proper rooting system in guar changes the physical properties of salt-affected soils as reported by Ashraf et al. (2005b). Studies on guar indicated that rotation of plants with high root volume, dry weight and high tap root diameter and length are tolerant to salinity; they have certainly high ability for deep tillage (Ashraf et al. 2006b). Rotation of salt tolerant plants like *Sesbania* with crops like wheat is also beneficial for phytoremediation. A field study conducted at BSRS–II, (NIAB, Faisalabad, Pakistan), indicated that rotation of the deep rooted plants species such as *Brassica* with Kaller grass improves porosity of the saline soil (Ashraf et al. 1999, 2006b). So the plants with active and strong rooting system can be perfectly used for the remediation of salt-affected soils.

Deep-rooted perennial grasses (such as *Cenchrus* and *Pennisetum* spp.) and legumes (*Acacia*) can improve the hydraulic properties of saline soils (Akhter et al. 2004). Observations from the field studies have revealed beneficial effects of root growth in saline soils during phytoremediation. Ashraf et al. (2006a) found that deep-rooted *Acacia* species ameliorate a low-permeability hard saline sodic soil which results in an increase in saturated hydraulic conductivity. *Acacia* roots penetrated as deep as 2 m as compared to 1.1 m in *Atriplex*. They proposed inclusion of deep-rooted crops such as *Acacia*, *Atriplex*, *Suaeda fruticosa* in mixed cropping systems as a potential biological drilling strategy to improve subsoil permeability (Table 15.3).

Studies conducted by Akhter et al. (2004) to examine cultivation of Kallar grass for different periods (from 1 to 5 years) on the soils with different characteristics has enlightened the fact that hydraulic permeability of the soil enhances in the upper depth (0–20 cm). The maximum value for hydraulic permeability is 55.6 mm d^{-1} after five years of cultivation of Kallar grass while it is minimum (0.35 mm d^{-1}) in uncropped plots. The increase is 159 fold after 5 years followed by 101.6, 43.8, 25.1, and 6.1 after 4, 3, 2 and 1 year of cropping, respectively. The increase in soil hydraulic permeability (K_{fs}) is due to the improvement in soil structural stability and porosity along with reduction of sodium adsorption ratio (SAR). After 5 years the K_{fs} rate of soil was the maximum with structural stability index value of 96%, porosity 42% and SAR value of 29. The main reason for these changes is due to the extensive root system Kallar grass possesses, which has the capacity to penetrate into the soil up to 1 m deep. In calcareous sodic soil, hydraulic permeability is maintained only during cropping and it decreases in non-cropped soil. A significant increase in hydraulic conductivity was noted by Gupta et al. (1989) who planted rice in highly alkaline soil. Meek et al. (1990) recorded higher infiltration rates with alfalfa as compared to cotton. To improve the physical properties of highly saline sodic soils, planting Kallar grass and other such salt tolerant plant species is recommended by many workers (Akhter et al. 1988; Gupta et al. 1989; Meek et al. 1990). Ilyas et al. (1995), however, reported that irrigation with poor quality caused adverse effects on hydraulic permeability of good soil. All these findings stress the fact that plantation with salt tolerant plant species on salt-affected soils is beneficial for improving hydraulic permeability of the soil due to which interactive processes like soil porosity, structural stability, organic matter and leaching of salts to lower surface of the soil increases.

Table 15.3 Influence of growing Kallar grass for different time periods on physical properties of a saline sodic soil

	Soil depth			
Growth year	(0–20 cm)	(40–60 cm)	(80–100 cm)	Mean (years)
Available water				
0	0.155	0.151	0.153	0.153
1	0.175	0.173	0.170	0.173
2	0.184	0.183	0.183	0.183
3	0.195	0.191	0.199	0.195
4	0.216	0.199	0.211	0.212
5	0.214	0.203	0.212	0.210
Mean (depths)	0.19	0.185	0.188	
Stability index				
0	31.9	18.6	32.6	27.7
1	57.6	36.0	34.1	42.6
2	66.8	64.7	71.2	67.6
3	68.4	50.5	55.4	58.1
4	119.4	66.8	76.5	87.6
5	150.6	47.3	90.8	96.2
Mean (depths)	82.5	47.3	60.1	
Bulk density (Mg m^{-3})				
0	1.62	1.73	1.68	1.68
1	1.61	1.72	1.60	1.64
2	1.58	1.65	1.59	1.61
3	1.55	1.59	1.56	1.56
4	1.54	1.53	1.55	1.54
5	1.53	1.53	1.54	1.53
Mean (depths)	1.57	1.62	1.59	
Porosity (%)				
0	28.9	34.6	36.5	36.7
1	29.1	35.3	39.7	38.0
2	40.4	37.7	40.0	39.4
3	41.5	40.1	41.3	41.0
4	42.3	41.5	41.9	41.9
5	42.8	42.2	42.4	42.2
Mean (depths)	40.8	40.8	40.3	

Values for different depths are means of three determinations

Due to root proliferation, soil bulk density (BD) reduced in all soils studied by us. However, Miyazaki (1996) has reported that soil BD is also changed by natural processes such as shrinkage with drying, consolidation with drainage and swelling with infiltration. He has pointed out that greater the BD of a soil (or alternately less the soil porosity) smaller is the saturated hydraulic permeability. According to Meek et al. (1992) an increase in BD from 1.7 to 1.89 Mg m^{-3} decreases the infiltration rate by four times and increases resistance to penetration by three times under cropping. A linear relationship has been found between $\log(K_{fs})$ and total porosity of the soil. The effectiveness of the biological model for improving soil physical properties such as soil bulk density is well documented (Toy and Shay 1987; Glauser et al. 1988; Costa et al. 1991). The cropping practices with Kaller grass for 5 years reduces the BD of soil by 8.9% compared to the uncropped plot. The BD reduction percentages are 2.3, 4.2, 7.1, 8.3 and 8.9% after 1 to 5 years respectively, compared to the uncropped plots (Table 15.3). Generally, growing of Kallar grass for 5 years has more pronounced effect on soil BD than other treatments. The values for soil BD decrease gradually from 1.67 to 1.52 Mg m^{-3} (Akhter et al. 2004). Our results indicated that change in soil BD differed with depth. The highest reduction of 3.1% was recorded for soil layer at 80–100 cm. The activity of rooting system is largely dominant in the upper depths (0–20 cm) after 1 year and roots are well distributed through the deepest soil depth (80–100 cm) during subsequent growth periods. Reduction in soil BD is a beneficial character for remediation of salt-affected soil as a result of which soil becomes suitable for conventional food crops.

Akhter et al. (2004) found that cultivation of Kallar grass enhances the water retention by soil at various tensions. More prominent effect is observed in the upper soil layers as compared to the deeper layers (Table 15.3). This is due to larger root activity in top layer of soil which leads towards the improvement in soil porosity, organic matter and other soil characteristics at a faster rate in the upper than the deeper layers of soil. Increase in soil water retention enhances availability of water for plants during cropping. For plants, water is available between field capacity and permanent wilting point (Cassel and Nielsen 1986), which can be estimated by measuring relative differences within and among soils. Availability of water (AW) significantly increases with cultivation of Kallar grass compared to uncultivated control (Akhter et al. 2004). The AW has a positive relationship ($r = 0.922^{**}$) with soil organic matter content. Water retention of 2 mm sieved soil samples increases with increasing organic carbon content at suctions from 10 to 1500 KPa. With an increase in organic matter (OM) soil water holding capacity increases, consequently AW increases (Bauer and Black 1992; Darwish et al. 1995). Results of Akhter et al. (2004) show strong correlations between AW and soil porosity, structural stability and hydraulic permeability which may affect the soil AW indirectly. Querejeta et al. (2000) has reported that addition of organic matter and mechanical terracing with sub-soiling increased the water storage of the soil profile which is due to improvement in soil structure and permeability.

There are many reports (Haynes and Francis 1993; Chenu et al. 2000) which indicate increases in aggregate stability by growing different crops in different types of soils. A positive relationship between soil carbon and increase in stable aggregates under cropping has been reported by Bruce et al. (1992). Considerable improvement has been recorded in soil structure by growing forages (Perfect et al. 1990; Haynes and Francis 1993). The reason for this is high root biomass, root length and dense rooting system. Akhter et al. (2004) studied effect of Kallar grass cultivation on structural stability of salt-affected soils which was measured as stability index in Kallar grass plots and noted that it was 54% of uncropped control plots after one year and increased up to 247% after 5 years (Table 15.3). Structural stability index increase rate was 13.4 per year after growing Kallar grass. However, soil depth significantly affected the soil structural stability index which was 82.5, 47.3 and 60.1 for the soil depths i.e., 0–20 cm, 40–60 cm and 80–100 cm, respectively (Table 15.3). Caron et al. (1992) also noted large increase in soil aggregate stability by growing bromegrass for 3 years. Different studies indicate that plantation of salt tolerant plants significantly influences the structural stability of the soils, particularly the water stable aggregates (Tisdal and Oades 1980; Ried and Goss 1981).

3 Changes in Soil Chemical Characteristics

Plants influence the chemical characteristics of the soils like soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR) and soil organic matter. Cultivation of salt tolerant plants improves all these characteristics. For example, Kallar grass grown on salt-affected soil up to 5 years significantly reduced the soil salinity up to 71% compared with control (Table 15.4). The highest reduction is 87% after 5 years of growth followed by 80, 84, 65 and 42% after 4, 3, 2 and 1 year, respectively, as compared to uncropped plots. Soil salinity markedly reduces from 16.2 to 2.1 dS m^{-1} (Akhter et al. 2003). The reduction in EC occurs chiefly due to the leaching of salts to deeper layers of the soil (Bhatti and Wieneke 1984). In contrast to above findings, field studies of 3 years with *Acacia* species and *Atriplex lentiformis* indicate that EC of the soil gradually decreases within 2 months after cultivation of *Acacia nilotica* and *Atriplex lentiformis*, while it increases in the case of *Acacia ampliceps* (Ashraf et al. 2006b). After 20 months of growth period, the highest EC values have been recorded for *Acacia ampliceps* followed by *Atriplex lentiformis* and *Acacia nilotica*. After 2 years of planting, a significant decrease in soil EC has been recorded which is maximum under *Acacia nilotica* plantation. Salinity of the soil fluctuated up to 36 months of planting but was lowest under *Acacia nilotica* (Ashraf et al. 2006a). Shekhawat et al. (2006) reported that the cultivation of *Haloxylon recurvum* reduced soil EC by 56 to 85% which varied with the depth of soil. Maximum decrease in soil EC took place in the upper layer (10–20 cm depth) and minimum at 40–50 cm soil depth. They reported that by cultivating *Suaeda nudiflora*, 60 to 85% change in soil EC took place. These changes were again higher in 10–20 cm soil layer and lower in 40–50 cm soil layer. Ashraf (2007) has also reported similar observations for *Suaeda fruiticosa* and *Atriplex*. Another study conducted by Yensen and Biel (2006) on the soil remediation through salt-conduction plants indicates that cultivation of *Distichlis*, *Spartina*, *Aeluropus* is beneficial to reduce the soil EC. Due to root activities, improvement in soil permeability has been recorded in soil under cultivation of all the plants mentioned above due to decreased EC in the upper soil layers. Therefore in order to reduce the soil salinity, cultivation of *Leptochloa fusca*, *Haloxylon recurvum*, *Suaeda nudiflora*, *Distichlis*, *Spartina* and *Aeluropus* can be recommended.

Results of the experiments on Kallar grass showed that soil pH decreases due to Kallar grass plantation (Table 15.4). The maximum decrease of 14.4% in pH was observed after 5 years with an average decrease rate of 0.229 units per year in case of

Table 15.4 Changes in chemical properties of a saline sodic soil by growing Kallar grass for different time periods

	Soil depth			
Growth year (T)	(0–20 cm)	(40–60 cm)	(80–100 cm)	Mean (years)
Electrical conductivity (dS m^{-1})				
0	22.0	22.2	12.5	18.9
1	12.6	14.0	6.3	11.0
2	7.4	9.7	3.1	6.7
3	3.2	3.8	2.4	3.1
4	2.8	3.8	4.8	3.8
5	2.0	2.1	3.2	2.4
Mean (depths)	8.3	9.3	5.4	
Soil pH				
0	10.4	10.5	10.4	10.4
1	9.3	9.2	9.5	9.5
2	9.1	9.4	9.3	9.3
3	9.2	9.5	9.4	9.4
4	9.1	9.6	9.7	9.3
5	8.9	8.9	9.0	8.9
Mean (depths)	9.3	9.5	9.6	
Sodium adsorption ratio				
0	185.5	187.2	114.7	162.5
1	70.6	97.6	78.7	82.3
2	65.9	91.5	74.1	77.2
3	32.5	53.0	35.8	40.4
4	25.8	47.5	25.0	32.8
5	20.7	41.2	25.4	29.1
Mean (depths)	66.9	86.4	59.0	
Organic matter (g kg^{-1})				
0	3.3	1.9	1.8	2.3
1	3.2	8.9	2.8	4.9
2	5.5	11.7	3.4	6.8
3	7.3	10.7	2.6	6.9
4	6.3	11.9	2.9	7.0
5	7.4	13.3	3.8	8.2
Mean (depths)	5.6	9.6	2.9	

Values for each depth are means of three replicates

growing Kallar grass. Usually, soil pH is different at different depths of soil profile which generally increases with increase in soil depth. Another study conducted with different species of *Acacia* and *Atriplex* indicated that soil pH did not change with the passage of time, which was alkaline at the outset of the trial, and was similar after three years of continuous cultivation (Ashraf et al. 2006a). However, reduction in soil pH was noted by Helalia et al. (1992) due to plantation with *Echinochloa stagninum* on saline soil. The reduction in soil pH may be directly related to root H^+, OH^-, HCO_3^- and organic anions which react with soil exchangeable ions or complexes, consequently disturbing cations and anions equilibria in the soil (Helyar and Poster 1989). It has also been observed that microbial activity increases by root respiration and by root exudates, as a result of which organic matter is added by vegetation which is responsible for change in soil solution quality thus changes in soil pH occur (Dormaar 1988). Uptake of NH_4^+ by the plants could also decrease soil pH considerably (Gorham et al. 1985). Efflux of H^+ from roots is commonly observed in roots of the plants growing under saline conditions which results in the reduction of soil pH. This reduction facilitates uptake of macro- and micro-nutrients due to which increase in growth and yield of the crop is expected when grown on these soils after phytoremediation.

Studies with Kallar grass indicated that SAR of soil decreases with the growth, however, reduction is more prominent in the upper layers of soil. Use of saltish water particularly in saline sodic soils raised the soil SAR at lower depths (80−100 cm) due to leaching of Na from upper layers and its ensuing accumulation in the middle soil depths (Table 15.4). Reduction in SAR in upper (0–15 cm) soil layers as compared with lower soil layers by cropping system has been found by many workers (Hussain et al. 1994; Chang and Leghari 1995). Kallar grass plantation up to 3 years significantly decreased the soil SAR, therefore, its cultivation was continued up to 5 years as a result of which a further reduction in SAR value of highly saline sodic soils was recorded. So, cultivation of Kallar grass on salt-affected soils is beneficial in removing and leaching of Na^+ from soil solution and exchange complex (Akhter et al. 2003). In contrast to these findings, Shekhawat et al. (2006) did not find any appreciable change in SAR with the cultivation of *Salsola baryosma*, *Haloxylon recurvum* and *Suaeda nudiflora*. However, studies with different species of *Acacia* and *Atriplex* also indicated that soil SAR decreased with cultivation of these species and effect of *Acacia nilotica* was more pronounced than others (Ashraf et al. 2006a). Similarly, results of the experiments conducted with *Sporobolus arabicus*, *Leptochloa fusca*, *Suaeda fruticosa*, *Atriplex lentiformis* and *Kochia indica* also confirmed that cultivation of salt tolerant plants is effective in reducing the soil SAR (Ashraf 2007).

It is a well established fact that vegetation cover on any type of soil increases organic matter (OM) content of the soil. So any type of vegetation on salt-affected soils is effective in enhancing its OM content. Akhter et al. (2004) reported that cropping with Kallar grass increased the OM of salt-affected soil significantly. Nelson et al. (1996; 1997) found that retention of OM would be improved if added after the reduction in soil SAR or ESP. Barzegar et al. (1997) observed improvement in soil aggregates stability due to the addition of plant residues which increased the OM content and reduced the soil sodicity. According to Akhter et al. (2004) addition of OM (8.2 g kg^{-1} of soil) after the cultivation of Kallar grass for 5 years, it reduced with the soil depth. Another study with *Acacia* species indicated that their cultivation on salt-affected soils increased the soil OM (Ashraf et al. 2006a). Similarly, Aganga et al. (2003) found an increase in soil OM with cultivation of *Atriplex* on salt-affected soils. *Suaeda salsa* plantation has been found effective in enhancing the OM content of saline soils (Zhao 1991). So, the cultivation of salt tolerant plants is beneficial in improving the OM of salt-affected soils.

4 Removal of Salts from Soil

Phytoremediation means the introduction of salt removing plant species on salt-affected soils to reduce salt content and to improve sustainability of salt affected soils. Salt-affected soils contain excessive Na^+ which is toxic to plants. A single plant of *Suaeda fruticosa* can remove 100 g of salt mainly by accumulating high amount of salts in its aerial parts. Shekhawat et al. (2006) conducted experiments with salt tolerant plants viz. *Salsola baryosma*, *Haloxylon recurvum* and *Suaeda nudiflora* and reported that after 3 months of growth period *Haloxylon recurvum* removed the highest Na^+ (17 g $plant^{-1}$) and maintained the highest biomass followed by *Suaeda nudiflora* (15.6 g $plant^{-1}$) and *Salsola baryosma* (9.6 g $plant^{-1}$). Zhao (1991) has reported that reduction in Na^+ was higher in the upper soil layer (20–30 cm) by *Salsola salsa*.

The root activity of halophytes in saline soils may affect the mobilization of native lime in the soil. Robbins (1986) reported that CO_2 produced due to the root respiration may be a one of the primary factors contributing to remediation of salt-affected lands, because in the presence of H_2CO_3, solubility of $CaCO_3$ increases. The released Ca^{2+} thus replaces the Na^+ from the soil exchange complex. Later along with other salts present in excessive amounts in the soil may be carried away from the root zone through excessive supply of good quality water. Shekhawat et al. (2006) have reported that cultivation of *Suaeda nudiflora* is effective in increasing the exchangeable Ca^{2+} in the soil, but most effective plant is *Haloxylon recurvum* followed by *Suaeda nudiflora* and *Salsola baryosma*. Plantation of these halophytes is effective in changing the EC, pH, exchangeable Na^+ and Ca^{2+} and exchangeable sodium percentage of the soils.

Qadir and Oster (2004) conducted 14 experiments to compare the remediation of salt-affected soils by chemicals and through vegetation and reported that soil amendment with gypsum reduced 62% of sodicity levels while it was 52% by phytoremediation. The reduction in sodicity due to phytoremediation of salt-affected soils may be less due to off season cultivation of salt tolerant plants. The change in results may be due to availability of limited irrigation during growth period, which is necessary for the downward movement of Na^+ otherwise phytoremediation is more effective than chemical amendments in reducing the soil salinity or sodicity.

Akhter et al. (2003) reported that cultivation of Kallar grass on salt-affected soils significantly reduces the soil Na^+ content (Table 15.5). The reduction in soil Na^+ is 70.5% after 5 years cultivation with Kallar grass when compared with uncultivated control plots. They reported that soil Na^+ content significantly decreases by 38.0, 62.0, 81.3, 86.6 and 84.5% as compared with control after 1, 2, 3, 4 and 5 years, respectively. The cation (Ca^{2+}, Mg^{2+} and K^+) content of soil also significantly reduces after 5-year growth of Kallar grass (Table 15.5). Before the cultivation of Kallar grass soil Ca^{2+}, Mg^{2+} and K^+ are 56, 16.8 and 28.5 mg kg^{-1} which reduces to 20.0, 3.6 and 11.7 mg kg^{-1} after 5 years of cropping with Kallar grass which are earlier 64.3, 78.6 and 80% respectively. However, reductions in these ions vary with soil depths which were 35.3, 40.0 and 45.5% Ca^{2+}, Mg^{2+} and K^+, respectively at 80–100 cm of soil depth and 11.8, 20.0 and 36.4% at 40–60 cm of soil depth higher

Table 15.5 Concentration of soluble cations in saturation extract of soil at different depths as a function of growing Kallar grass for different time periods

	Soil depth			
Growth year	(0–20 cm)	(40–60 cm)	(80–100 cm)	Mean (years)
Na^+ (me L^{-1})				
0	207	226	128	187
1	116	136	96	116
2	73	101	40	71
3	26	38	40	35
4	18	38	16	25
5	23	46	18	29
Mean (depths)	77	98	56	
Ca^{2+} (me L^{-1})				
0	3.7	2.6	2.0	2.8
1	2.0	2.0	1.9	2.0
2	1.3	1.4	0.4	1.0
3	0.9	0.7	1.2	0.9
4	0.6	1.0	0.5	0.7
5	1.4	1.0	0.6	1.0
Mean (depths)	1.7	1.5	1.1	
Mg^{2+} (me L^{-1})				
0	1.8	1.3	1.0	1.4
1	0.5	1.0	0.6	0.7
2	1.2	1.1	0.2	0.8
3	0.4	0.3	1.3	0.7
4	1.1	1.5	0.4	1.0
5	0.4	0.3	0.3	0.3
Mean (depths)	1.0	0.8	0.6	
K^+ (me L^{-1})				
0	1.3	1.8	1.3	1.5
1	3.0	0.5	0.5	1.3
2	0.7	0.7	0.7	0.7
3	0.7	0.7	0.7	0.7
4	0.3	0.5	0.3	0.4
5	0.4	0.2	0.2	0.3
Mean (depths)	1.1	0.7	0.6	

Values are means of three replicates

in the levels of Ca^{2+}, Mg^{2+} and K^+, respectively, in comparison with surface layer (0–20 cm).

In another study conducted by Ashraf et al. (2006a) with five *Acacia* species and *Atriplex* as check indicated that Na^+ decreased with the cultivation of different species which increased with increase in time and was maximum after 3 years while increase in Ca^{2+} and K^+ was observed in soil due to the cultivation of different *Acacia* species which was the highest after 3 years of their cultivation. Krishnapillai and Ranjan (2005) found reduction in soil Na^+ contents due to the cultivation of *Atriplex* in salt-affected soils. Some reports (Hussain et al. 1994; Chang and Leghari

1995) show that cultivation of salt tolerant plants helps restore soil structure and permeability. They do this through deep penetration of their roots and solubilization of soil $CaCO_3$ thereby leading to enhanced salt leaching and reduced salinity and alkalinity of saline or sodic soil. These reports also indicate that many economic crops and native halophytic plant species resulted in high removal of soil Na^+, effective in mobilization of naturally occurring insoluble $CaCO_3$, reduces the soil pH by increasing CO_2 solublization and its release due to the activities of plant roots. So, cultivation of halophytes and grasses are effective in reducing the soil salinity and alkalinity through different mechanisms.

Salt-affected soils in addition to cations also contain excessive anions like Cl^-, $SO_4{}^{2-}$ and $HCO_3{}^-$ which are toxic to plants and reduce growth and plant productivity. Cropping with halophyte grasses and other plants is helpful in removing these anions from soil profile (Crescimanno et al. 1995). It was found that cultivation of Kallar grass is effective in reducing the anions significantly (Akhter et al. 2003). The reduction in Cl^-, $SO_4{}^{2-}$ and $HCO_3{}^-$ was 88.4, 88.6 and 90.9% respectively after 5 years of Kallar grass cultivation. Levels of Cl^-, $SO_4{}^{2-}$ and $HCO_3{}^-$ in soil solution

Table 15.6 Concentration of soluble anions in saturation extracts of soil at different depths as a function of growing Kallar grass for different time periods

	Soil Depth			
Growth year	(0–20 cm)	(40–60 cm)	(80–100 cm)	Mean (year)
Cl^- (me L^{-1})				
0	62.1	72.5	40.7	58.4
1	32.7	44.7	33.6	37.0
2	20.3	29.3	16.6	22.1
3	9.7	12.6	9.0	10.4
4	8.2	11.6	7.5	9.1
5	6.0	8.0	6.0	6.8
Mean (depth)	23.2	29.8	18.8	
$SO_4{}^{2-}$ (me L^{-1})				
0	46.7	76.0	28.8	50.8
1	55.2	71.3	24.2	50.2
2	22.2	39.4	13.5	25.0
3	12.5	16.2	9.4	12.7
4	10.2	13.8	10.0	11.3
5	5.6	10.1	4.7	6.8
Mean (depth)	25.4	37.8	15.1	
$HCO_3{}^-$(me L^{-1})				
0	103.4	101.4	68.3	91.0
1	36.1	50.5	15.4	34.0
2	23.1	37.8	11.0	24.0
3	12.3	15.8	14.8	14.3
4	6.8	8.0	13.4	9.4
5	6.2	3.6	15.0	8.3
Mean (depth)	31.3	36.2	22.9	

Values are means of three replicates

reduced at rates of 0.449, 0.435 and 0.467 me L^{-1} $year^{-1}$. Reductions in concentration of these anions varied with the soil depth and the highest reduction 36.9, 60.1 and 36.7% (Cl^-, SO_4^{2-} and HCO_3^-, respectively) was noted at 80–100 cm soil depth followed by 22.1, 32.8 and 13.5% at soil depth of 40–60 cm when compared with the soil depth of 0–20 cm (Table 15.6). According to Qadir and Oster (2004) soil chemical properties have significant correlations with the removal of salts by the planting of salt tolerant plants, because the changes in both soil EC and pH depend on the concentrations of Na^+, Ca^{2+}, Mg^{2+}, K^+ and Cl^-, and HCO_3^- present in the salt-affected soils. Similarly a high correlation of SAR exists with most of the soil chemical properties indicated above. However, Akhter et al. (2003) have reported a negative correlation between all chemical properties and soil organic matter content mentioned above.

5 Improvement in Soil Fertility

There are many reports (Ashraf et al. 2006a, b; Qadir et al. 2006; Shekhawat et al. 2006) which indicate that phytoremediation of salt-affected soils improves their fertility. After phytoremediation, availability of nutrients to the subsequent crop should increase. Qadir et al. (2006) compared the effect of phyto- and chemical remediation of salt-affected soils for nutrient availability to the subsequent crops and reported that cropping with Kallar grass, *Sesbania* and sordan grass cultivation for 15 months significantly increased P, Zn and Cu availability while addition of gypsum in the non-cropped soil reduced the availability of these inorganic elements. Nitrogen (N) contents of the soil increased where *Sesbania* was cultivated which was due to nitrogen fixing ability of the crop. According to their findings, the amount of N increased from 0.49 to 0.53 g kg^{-1} in 15 months, however, they did not note any appreciable change in soil K^+ contents. Cultivation of *Sesbania* for 45 days and then its use as green manuring, enriched the salt-affected soils by adding up to 122 kg N ha^{-1} which was available for the next crop. Evidence of N conservation has also been provided by other phytoremediation-oriented crops like Kallar grass (Malik et al. 1986). However, N losses via NO_3 leaching were recorded during the remediation of saline sodic soils with chemical amendment like gypsum (Qadir et al. 1997). Singh and Gill (1990) conducted experiments with tree species viz. *Prosopis juliflora*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Albizia lebbeck*, and *Terminalia arjuna* and reported that a considerable reduction in pH and increase in organic matter (organic C) content, and available P and K content in 0–15 cm soil depth occur due to the cultivation of these species.

Appreciable changes in soil microbial biomass were recorded by the plantation of halophytes especially leguminous plant species like *Acacia* and *Sesbania* (Batra et al. 1997; Ashraf et al. 2006a). Addition of microbial biomass in soils is beneficial to increase the soil organic matter and nutrients. The microbial activity in the salt-affected soils is often very low due to the absence of vegetation cover. It is measured as dehydrogenase activity (DHA) showing how much microbial population is present. As a result of CO_2 generation through respiration and decomposition of organic matter, overall microbial activity can also be estimated in the soils under cultivation (Włodarczyk et al. 2002). Batra et al. (1997) studied chemical and phytoremediation effects on DHA of the saline soil. They used gypsum (14 Mg ha^{-1}), Karnal grass, sorghum + gypsum, rice + Sesbania + gypsum for sodic soil, and found that DHA was greater in those soils where Karnal grass was cultivated. Earlier, Rao and Ghai (1985) also reported significant increase in DHA of sodic soil by the permanent cultivation of grasses. Rao and Pathak (1996) reported that green manuring with *Sesbania* increased DHA and urease activity of salt-affected soils. Garg (1998) studied changes in sodic soil with the cultivation of four tree species, i.e., *Acacia nilotica*, *Delbergia sissoo*, *Prosopis juliflora* and *Terminalia arjuna* and reported that *Delbergia sissoo* and *Prosopis juliflora* were more effective in terms of producing high biomass production and reducing soil sodium contents. Higher microbial activity in the upper 0–60 cm soil depth was recorded due to cultivation of these species because of humus accumulation by the decay and decomposition of plant litter and root decay that led to increase in soil organic carbon. The rate of soil carbon increase was low for the first 2–4 years, thereafter it was exponential from 4–6 years and a plateau during the period from 6 to 8 years. Bhojvaid and Timmer (1998) also found that cultivation with *Prosopis juliflora* on sodic soil increased organic carbon of the upper 1.2 m soil layer from 11.8 to 13.3 Mg C ha^{-1} after 5 years, 34.2 Mg C ha^{-1} after 7 years and 54.3 Mg C ha^{-1} after 30 years. Average annual increase rate in soil organic carbon was 1.4 Mg ha^{-1} in 30 years. Plants used for phytoremediation of salt-affected soils showed wide range in their decomposition and turnover rates as a result of C stored in the soil (Torn et al. 1997; Kiem and Koegel-Knabner 2003; Sahrawat 2004; Sariyildiz and Anderson 2003; Six et al. 2002). Sahrawat (2003) and Sahrawat et al. (2005) reported that green manuring in salt-affected soils also increases the soil organic matter through microbial activity which affects the C sequestration via soil inorganic C.

6 Selection of Plants for Phytoremediation

Plants having capability to remove the maximum quantity of salts by producing higher biomass with some economic importance are mainly selected for phytoremediation (Qadir and Oster 2002). This selection is by and large based on their ability to resist to the high levels of soil salinity. Several plant species including, grasses, shrubs and trees are being used for phytoremediation of salinised soils. The plants identified at NIAB, Faisalabad, Pakistan are summarized in Tables 15.7 and 15.8. Kallar grass has been widely recommended by many workers (Kumar and Abrol 1984; Malik et al. 1986; Akhter et al. 2003), however, different workers recommend different plants keeping in view the soil texture, and physico-chemical properties of salt laden soils. Oster et al. (1999) and Robbins (1986) worked on grasses and recommended Bermuda and Sordan grasses respectively, similarly *Sesbania* and alfalfa have been recommended by Ahmad et al. (1990) and many others. These produce high biomass and have high salt tolerance and are recommended for the remediation of salt-affected soils. Other species are shrubs like *Kochia scoparia* (Garduno 1993), *Atriplex* and *Maireana* (Barrett-Lennard 2002), *E. crusgalli* (Aslam et al.

Table 15.7 Salt tolerant grasses and shrubs identified for phytoremediation

	Root zone salinity causing 50% yield reduction	
Plant species	EC (dS m^{-1})	% salt
Grasses		
Leptochloa fusca	22.0−14.6	1.41−0.93
Sporobolus arabicus	21.7	1.39
Cynodon dactylon	21.0−13.2	1.34−0.84
Hordeum vulgare	19.5−10.0	1.25−0.64
Sorghum. vulgare	16.7−15.0	1.07−0.96
Panicum antidotale	16	1.02
Echinochloa crusgalli	15.9	1.02
Polypogon monspeliensis	13.7	0.88
Avena sativa	11.8−9.1	0.76−0.58
Lolium multiflorum	11.2	0.72
Echinochloa colona	11.2	0.72
Desmostachya bipinnata	9	0.64
Panicum maximum	9.0−8.5	0.58−0.54
Sorghum halepense	7	0.45
Shrubs		
Suaeda fruticosa	48	3.07
Kochia indica	38	2.43
Atriplex nummularia	38	2.43
Atriplex amnicola	33	2.11
Atriplex lentiformis	23	1.47
Atriplex undulate	22.5	1.44
Atriplex crassifolia	22.5	1.44
Sesbania Formosa	21.4	1.37
Beta vulgaris	19	1.22
Lotus carniculatus	16.7	1.07
Trifolium alexandrinum	15.8	1.01
Sesbania aculeate	13	0.83
Hasawi rushad	12.5	0.8
Medicago sativa	13.2−12.2	0.84−0.78
Sesbania rostrata	12	0.77
Macroptilium atropurpureum	12	0.77
Trifolium resupinatum	11.6	0.77

1987), *Portulaca oleracea* (Grieve and Suarez 1997), *Salicornia bigelovii* (Glenn et al. 1996), and *Glycyrrhiza glabra* (Kushiev et al. 2005). Many trees have also been recommended. Phytoremediation with trees and grasses is beneficial because these can be utilized as fodder, timber, fuel (Chaudhry and Abaidullah 1988; Sandhu and Qureshi 1986). Qureshi et al. (1993) suggested agroforestry systems consisting of mainly tree species and cultivation of salt tolerant crop varieties, as the most economically viable approach for phytoremediation because production of fuel-wood, and timber is a demand of local market and cultivation of grasses can fulfill fodder shortage and fetch reasonable prices in local markets.

Table 15.8 Salt tolerant vegetables and trees identified for phytoremediation

	Root zone salinity causing 50% yield reduction	
Plant species	EC (dS m^{-1})	% salt
Vegetables		
Aster tripolium	31.7	2.03
Brasssica napus	19.5	1.25
Trigonella foenum–graceum	19.2	1.23
Spinacea oleracea	14.8	0.94
Medicago falcata	13.4	0.86
Brassica carinata	12.5	0.8
Brassica juncea	12.4−8.44	0.79−0.54
Lactuca sativa	9.9	0.63
Brassica campestris	9.8	0.63
Eruca sativa	9.4	0.6
Coriandrum sativum	5.7	0.37
Trees		
Acacia sclerosperma	38.7	2.48
Acacia ampliceps	35.7	2.28
Prosopis juliflora	35.3	2.26
Prosopis chilensis	29.4	1.88
Casuarina obesa	29.2	1.86
Acacia victoriae	28.3	1.81
Eucalyptus microtheca	27.9	1.78
Acacia nilotica	27.9	1.78
Acacia acuminate	27.7	1.77
Acacia cambagei	27.7	1.77
Eucalyptus striaticalyx	26.2	1.68
Acacia salicina	24.5	1.57
Prosopis cineraria	24.4	1.56
Casuarina glauca	24.4	1.56
Prosopis tamarugo	22.7	1.45
Acacia calcicola	19.9	1.27
Acacia coriacea	18.2	1.16
Cassia nemophila	16.8	1.07
Cassia sturtii	15.8	1.01
Acacia saligna	15.7	1
Acacia bivenosa	13.7	0.88
Acacia subtessarogna	13.7	0.88
Leucaena leucocephala	12.4	0.79
Acacia kempeana	11	0.7
Acacia aneura	9.5	0.61
Acacia cunnighamii	9.4	0.6
Acacia holosericea	9	0.78
Acacia adsurgens	4.3	0.27
Acacia validinervia	1.7	0.11

7 Conclusion

Most of the relevant literature and experiments conducted by different scientists have shown that phytoremediation is the most economical approach through which salt-affected wasteland can be successfully utilized for plant production. Toxic ions like Na^+ and Cl^- are removed by the salt tolerant plants used for phytoremediation, and addition of Ca^{2+}, K^+, P and N in the salt-affected soils occurs thereby improvement in the soil physico-chemical properties takes place and soils become fertile for subsequent crops.

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