Sanjay Arora · Atul K. Singh
Y.P. Singh *Editors*

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Foreword

Salinity and sodicity of soil is a global problem that extends across all continents in more than 100 countries of the world, presenting a major threat to farm agricultural production, leading to adverse implications for food security, environmental health, and economic welfare. The remediation of salt-affected lands and their management will go a long way in meeting the desired 57% increase in global food production by the year 2050. Amelioration of saline and sodic soils has been predominantly achieved through the application of chemical amendments. However, amendment costs have increased prohibitively over the past two decades due to competing demands from industry and reductions in government subsidies for their agricultural use in several developing countries. Also, the availability of chemical amendments, such as gypsum, that come from minerals is a problem. Saline soil improvement needs excessive amounts of good quality water to wash salts as an ameliorative measure. In many countries in arid and semiarid regions where rainfall is scanty and the availability of good quality waters is a problem, this method of reclamation does not seem to be feasible. However, alternate biological methods such as planting the soil with salt-tolerant plants where salts are taken up by these plants and removed from the soil or exchanged through biological processes can be used. Bioremediation is considered as a promising option as it requires low initial investments and improves the soil quality and the crop produce. Halophilic microorganisms are organisms that grow optimally in the presence of high salt concentrations. These have high potential for bioremediation applications and have been reported by several workers. The applications of halophilic bacteria trigger recovery of salt-affected soils by directly supporting the establishment and growth of vegetation in soils stressed with salts.

The biotic approach ("plant-microbe interaction") for overcoming salinity/sodicity problems has recently received considerable attention throughout the world. Bacteria are most commonly used in the bioremediation of soils. Vesicular-arbuscular mycorrhiza or VAM fungi is also found to be effective in alleviating salt stress and increasing availability of nutrients to the plants. Bioremediation, including phytoremediation approaches for management of saline, sodic and coastal saline, and waterlogged soils, seems needed. Bioremediation and management of vast areas of salt-affected soils involve considerations of economic viability, environmental sustainability, and social acceptability of different approaches. Phytoremediation strategies can be economically beneficial if there is market demand for the selected crops, grasses, or trees, or if they are useful locally at the farm level. However, in any economic analysis of sodic soil amelioration, it is also important to consider the long-term benefits of improvements made to the soil and the environment. This all will help in bioremediation of saline soil and improvement of crop yields, and in turn will help in uplifting the socioeconomic status of the farming community. However, there are several opportunities and challenges for the future of bioremediation techniques for the effective reclamation of salt-affected soils. In this book, the information and technologies developed for bioremediation and management of salt-affected soils are compiled with an emphasis on characterization, reclamation, microbial and vegetative bioremediation, and management technologies for salt-affected and waterlogged sodic soils.

In this book, attempts have been made to address a wide range of issues related to principles and practices for rehabilitation of inland and coastal salt-affected soils as well as waterlogged saline and sodic soils. Several site-specific case studies typical to the saline and sodic environment, including coastal ecologies, sustaining productivity, rendering environmental services, conserving biodiversity, and mitigating climate change, are included and described in detail. Written by leading researchers and experts of their specialized fields, this book, though in an Indian context, will serve as a knowledge center for experts in management of salt-affected soils but also for researchers, policy makers, environmentalists, students, and academics from all parts of the world. Further, it will also help reverse salinity development to ensure the livelihoods of resource-poor farming families living in harsh ecologies including coastal areas which are more vulnerable to climate change.

I congratulate and extend my appreciation to the editors for conceptualizing and developing the framework of this publication, and the authors for summarizing their wealth of knowledge and experiences. I sincerely hope and believe that the information contained in this book will provide new insight to researchers, extension workers, field officers, and others involved in reclamation and management of salt-affected soils.

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Preface

In the past, the increasing needs of a growing population for food, fuel and fiber were met by cultivating progressively larger areas of land and by intensifying the use of existing cultivated land. Under circumstances with diminishing good-quality lands and stagnating crop yields, the food demands of an increasing population must be met through the reclamation and management of degraded lands, including salt affected lands. Salt-affected soils cover about 6 % of the world's lands, which is mainly due to either natural causes or human-induced causes that affect about 2 % (32 million ha) of dryland farmed areas and 20 % (45 million ha) of irrigated lands globally. In India, about 6.73 million ha of land are affected by salts. To overcome this problem, several researchers have advocated the biological approach to improve these lands for cultivation. Innovative technologies in managing marginal salt affected lands merit immediate attention in view of climate change and its impact on crop productivity and the environment. The management of degraded land on a sustainable basis offers an opportunity for the horizontal expansion of agricultural areas in the India. During the last three decades, a number of strategies to ameliorate different kinds of marginal lands, including salt affected areas, have been developed. Adequate knowledge in diagnosis and management technologies for saline and alkali lands is essential to obtain maximum crop production from these resources. Bioremediation is one of the eco-friendly approaches for improving the productivity of salt affected soils.

This book attempts to gather and discuss the information and technologies developed for the bioremediation and management of salt affected soils. The emphasis in this endeavour was on characterization, reclamation, microbial and vegetative bioremediation and management technologies for salt affected and waterlogged sodic soils. This book contains 14 chapters that highlight the significant environmental and social impacts of different ameliorative techniques for salt affected soils. Bioremediation, including phytoremediation approaches for managing saline, sodic and coastal waterlogged soils, is the major emphasis. Agronomic practices, including agroforestry at different scales, with case studies in India are also part of the book. The book summarizes and updates information about the distribution, reactions, changes in bio-chemical properties and microbial ecology of salt affected soils in India that can be useful globally. Furthermore, it addresses the environmental and socio-economic impacts of reclamation programs with particular emphasis on the impacts on agricultural production and rehabilitation of degraded lands, vis-a-vis the economics of farmers. The decision-making process related to the reclamation and management of vast areas of salt affected soils involves considerations of the economic viability, environmental sustainability, and social acceptability of different approaches. The book contains the latest case studies and applied techniques of bioremediation of salt affected soils.

Overall, we hope the book facilitates future examinations of large scale adoptions of effective techniques by providing summaries of existing data and research related to the restoration of degraded lands through halophyte plant species, diversification of crops, and introduction of microbes for remediation of salt affected soils, and offering a framework for better understanding and identifying the future challenges.

We are thankful to the authors who are experts in their respective fields, and have written a comprehensive and valuable resource for researchers, academicians and students interested in the fields of soil science, environmental science, microbiology, remediation technology, and plant and soil stresses.

Lucknow, India

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Current Trends and Emerging Challenges in Sustainable Management of Salt-Affected Soils: A Critical Appraisal

Dinesh Kumar Sharma and Anshuman Singh

1 Introduction

Land degradation caused by the physical, chemical and biological processes severely limits the productivity of agricultural lands (Bai et al. 2008; WMO 2005). Anthropogenic activities accentuate the extent of damage caused by these natural processes and often result in severe deterioration in soil quality rendering the affected lands unsuitable for agricultural uses (Fitzpatrick 2002). Soil erosion caused by water and wind, surface crusting and soil compaction are the important physical agents causing degradation. Similarly, salinization, acidification and depletion of soil organic carbon and nutrients are the major chemical processes responsible for the decrease in soil productivity. Both physical and chemical factors coupled with intensive agricultural practices characterized by the heavy and indiscriminate use of water and fertilizers impair the soil health as evident by decreased activities of beneficial macro- and microflora and fauna in intensively cultivated and degraded soils. While currently over 2.5 billion people are directly affected by different kinds of land degradation, a large chunk of global population (~1 billion) in underdeveloped and developing countries is said to be at high risk (WMO 2005). On a geological time scale, both soil degradation and formation processes remain in steady-state equilibrium. The human quest to produce more food, for example, by land clearing and irrigation development, alters this equilibrium and shifts the balance in favour of degradation processes. Anthropogenic land degradation often occurs at a much rapid rate than the loss caused by geohydrological processes and, in extreme cases, leads to unforeseen consequences such as desertification and the consequent abandonment of agricultural lands (Fitzpatrick 2002). Besides widespread land degradation, a multitude of emerging constraints pose huge stumbling

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blocks to the efforts required to maintain the present and the projected food requirements. Some of these constraints include ever-shrinking availability of productive agricultural lands (Garnett et al. 2013; Lambin and Meyfroidt 2011), pervasive land use (Foley et al. 2005; Lotze-Campen et al. 2008), deforestation and biodiversity erosion (Harvey et al. 2008; Lambin and Meyfroidt 2011; Rounsevell et al. 2003), freshwater scarcity (Simonovic 2002; UN-Water 2006), climate change (Mendelsohn and Dinar 1999; Schmidhuber and Tubiello 2007) and dietary transition in many parts of the world (Kearney 2010).

In the second half of twentieth century, dramatic improvements in global food production were largely made by bringing additional lands under cultivation through the use of high-yielding varieties, chemical fertilizers and irrigation. In a rapidly changing scenario, this approach may not be viable; good quality land and freshwater resources are becoming scarce due to increased completion for other uses and massive land degradation impairing the productivity of vast tracts of agricultural lands (Garnett et al. 2013; Godfray et al. 2010). The alarming rate of natural resource degradation is evident by the fact that about 25 % of the global soil and water resources lie in a deteriorated state with adverse implications for the food security of a burgeoning world population (FAO 2011). World over, human-induced pervasive land use (e.g. shifting cultivation, deforestation, intensive cropping, infrastructure development) has proved fatal to vital ecosystem functions and services, soil health and global carbon and water budgets which are key to the sustainable human future (Foley et al. 2005; Lotze-Campen et al. 2008). The growing diversion of productive lands to raise the biofuel crops such as maize and sugarcane may further accentuate the problem of food insecurity. The USA, for example, presently accounts for over 70 % of global maize exports, and the soaring number of bioethanol production distilleries in this country could distort the global maize trade resulting in drastically reduced maize supplies to many developing countries (Escobar et al. 2009).

The need to ensure food security while maintaining the ecological balance requires that protected territories and forests are not encroached for crop production. The contemporary trends in many developing countries, however, sharply deviate from this prerequisite as efforts to maintain sufficient food reserves have often accelerated deforestation and land conversion. It is argued that a judicious mix of innovative crop production strategies, land-use zoning, more investments in agricultural research and development and policy changes could be a strategic choice to overcome the likely trade-off between food production and land loss (Lambin and Meyfroidt 2011). The fact that agricultural intensification accentuated the problems of land degradation, deforestation and biodiversity depletion is beyond any doubt (Harvey et al. 2008; Rounsevell et al. 2003). Besides intensive land use, globalization, industrialization and sociocultural changes are also responsible for a transition from the traditional diversified farming systems to the mechanized and profit-oriented agricultural production (Harvey et al. 2008). Agricultural land use profoundly impacts the ecological balance as evident from the long-term changes in soil quality, water balance and biodiversity (Rounsevell et al. 2003). Considering the fact that intensive land management is not compatible with the environmental integrity, alternative approaches such as integrated landscape management (Harvey et al. 2008) and sustainable intensification of agriculture (Garnett et al. 2013) have been suggested to ensure a balance between agricultural production and environmental sustainability. Sustainable intensification of agriculture is essentially based on four principles of increasing food production while lessening the pressure on the existing croplands as well as arresting the harmful spillover effects of energy-intensive cropping. First, the existing loopholes in food supply systems necessitate the concerted efforts to curtailing the food wastages, developing efficient supply chains and moderating the demand for water- and energy-intensive foods such as meat and dairy products. Second, technological interventions to address the current yield gaps in major crops should duly consider the environmental sustainability concerns. Third, in some cases, even minor yield reductions or land reallocation may be desirable to ensure marginal improvements in environmental quality. Finally, the merits and demerits of each available option (i.e. conventional, high-tech, agro-ecological and organic) should be cautiously weighed so as to devise location- and context-specific strategies for sustainably harnessing the productivity of agricultural lands (Garnett et al. 2013).

The contemporary concerns for sustainable development place a critical emphasis on water which could be the most critical natural resource for sustainable human living in the twenty-first century (Lazarova et al. 2001; Islam et al. 2007). Rapid growth in world population and the global economic transformation have substantially increased the demand for fresh water (Simonovic 2002) resulting in a 'freshwater crisis' with 20 % of the global population lacking access to the safe drinking water (UNEP 2002). Presently, severe water stress affects large parts of China and India. As irrigated agriculture accounts for a major chunk of total water use in these countries, water shortages are decreasing their capacity to produce enough food (UN-Water 2006). Despite having about 17 % of the world's population, India is endowed with only 0.04 % of the world's available water resources. Annual per capita water availability in India, extremely low in some regions (e.g. 300 m^3 in Sabarmati basin) but very high (e.g. 13,400 m^3 in Brahmaputra-Barak basin) in others, has decreased from 4000 m^3 to 1869 m^3 in the last two decades and is expected to decrease below 1000 m^3 by 2025 (Babel and Wahid 2008). At present, the total global water resources are calculated at 110,000 km^3 $year^{-1}$, of which green (water in the soil) and blue (water in rivers and groundwater) water pools constitute roughly 64 % and 36 %, respectively. Out of total global water availability, the total amount of water required to produce food is about 5200 km^3 $year^{-1}$. Out of this amount, approximately 46 % is used to produce meat and meat products, while about 23 % goes in cereal production. The huge differences in water use in production of different commodities thus necessitate careful analysis to understand the global water and energy dynamics in relation to total calorie intake, environmental footprint and national food policies of different countries (Lopez-Gunn and Ramón Llamas 2008).

The high vulnerability of agriculture to climate change, particularly in developing countries where majority of the farmers have poor adaptive capacity (Mendelsohn and Dinar 1999), is attributed to both direct and indirect impacts. Among the direct impacts, anticipated changes in rainfall pattern; elevated mean surface temperature;

increased frequency of droughts, floods and storms; and sea level rise are well documented. While marked shifts in temperature and precipitation will significantly increase the cropland area in high-altitude temperate regions, low-altitude regions in developing countries will face reduced availability of prime agricultural lands. Increased frequency of extreme events such as heat waves, floods and droughts will prove more catastrophic in environmentally degraded areas. The indirect impacts of relevance to global food security will be due to reduced food supplies, higher food prices, difficulties in safe access to food and a range of food safety issues (Schmidhuber and Tubiello 2007). World over, major shifts in food consumption with a gradual transition from food grains to diversified diets are increasingly becoming noticeable. Globalization-led structural changes in agro-industrialization and food marketing coupled with a range of socio-demographic factors account for this dietary (essentially nutritional) transition (Kearney 2010). Significant increase in consumption of processed food and dairy products, meat and fish ascribed to the higher purchasing power is bound to increase the pressure to produce more nutritious food (Godfray et al. 2010) often at the cost of a high environmental footprint owing to the increased use of water and energy-intensive inputs in food production, processing and transport (Rijsberman 2006; Godfray et al. 2010).

The concerns to feed an exponentially growing world population on the one hand and arresting the shrinkage of productive land resources on the other have enhanced the scientific and political attention to tap the potential of degraded lands. This consideration stems from the fact that even marginal yield gains from such deteriorated land resources (e.g. salt-affected lands) would make a large difference to the global food output. This line of argument is even more relevant to those agricultural regions where heavy investments have been made to improve the irrigation and drainage infrastructure. While long-term strategic plans to improve the land quality will remain all important, immediate focus should be on provisional measures of salinity mitigation to harness the dividends in offing (Qadir et al. 2014). Keeping in view the fact that land is a finite resource, strategic rehabilitation plans for the degraded lands as well as the technological measures to arrest the likely deterioration inland quality in the future will be equally important. A variety of approaches—engineering, agronomic and biological—are suggested to restore the productivity of marginal and degraded lands. Depending on context-specific requirements and the likely stumbling blocks in the technology implementation, a well thought of blend of available technological interventions will give the best results. This article presents an overview of salinity research in India in the last five decades. Based on a critical review of literature, current global trends in the sustainable management of salt-affected lands are presented, and their practical utility with special reference to developing countries is discussed.

2 Salt-Affected Lands: Social and Environmental Costs

Although a bulk of salt-affected soils have originated due to natural causes, the recent salinization trends are warning signals in that human-induced salinity affects about 2 % of the global dry lands and 20 % of the irrigated lands. Notwithstanding the disproportionately small share of irrigated land (~15 %) in the total cultivated land, it is worrisome that unabated salinization continues to despair their high productivity which is almost two-fold higher than the yields obtained in dry lands (Munns 2005). The annual rate of new irrigation-induced salinization is estimated at 0.25–0.5 million ha globally (Wicke et al. 2011). Massive secondary salinity in cultivated lands was partly responsible for the collapse of Mesopotamia civilization in the Euphrates and Tigris river valleys. It is believed that faulty irrigation practices caused excessive salinity build-up in cultivated lands such that wheat and even salt-tolerant barley crops failed to grow (Pitman and Läuchli 2002). Available evidences are ample to prove that some of the fertile regions of the world have been suffering from salinity threat for many decades. In many dryland (Fitzpatrick 2002; Lambers 2003; Stirzaker et al. 1999) and irrigated (Abdel-Dayem et al. 2007; Datta and De Jong 2002; Fayrap and Koc 2012; Houk et al. 2006; Qureshi et al. 2008) regions of the world, the problem of secondary salinity is becoming severe with each passing day. Consequently, some of the highly productive tracts, once the backbone of national food security in many countries, have become unproductive.

Dryland salinity is a major threat to arable cropping in Australia where it affects about 1.8 million ha agricultural lands in the wheat belt of Western parts. Given the current trends, over 8 million ha of productive soils in the region could face huge salinity risks by 2050. Land clearing for agricultural development replaces the native perennial vegetation by the annual crops and alters the water balance such that considerably high deep percolation occurs beyond the crop root zone (Lambers 2003). Owing to their shallow rooting depth and seasonal growth, the long-term average water use by annual crops and pastures is far below that of perennial trees and shrubs. The average deep drainage in drier regions has increased from <0.1 mm year^{-1} in the preclearing phase to >10 mm year^{-1} at present. Unrestricted water leakage beyond the root zone causes gradual rise of the water tables (~0.5 m year^{-1}) resulting in salt movement from subsurface to the surface layers (Stirzaker et al. 1999). A set of measures involving the improved agronomic practices to increase crop water use, integration of perennial pastures into crop rotations, engineering solutions to dispose the excess surface and/or groundwater and planting of trees and shrubs are suggested to tackle dryland salinity menace (Stirzaker et al. 1999). The main priority should, however, always be to raise perennial plantations to arrest the water table rise. Depending on the location-specific needs, either herbaceous (pastures or crops) or woody (trees and shrubs) species, may be grown. In areas having shallower water table, the use of salt-tolerant plants and drainage interventions (e.g. deep open drains) may be necessary (Pannell and Ewing 2004).

Sustainable productivity of rice-wheat cropping system, practiced in about 12 million ha area in South Asia, is of paramount importance to the regional food security. In recent past, however, decreasing factor productivity and yield stagnation ascribed to different biotic and abiotic constraints have markedly reduced the profits and raised concerns over the sustainability of the system (Fujisaka et al. 1994). In this context, development of the vast tracts of waterlogged saline lands due to excessive water use in many parts of Northwest India has also emerged as a formidable constraint to the viability of this system. In addition to altering the agro-ecological balance, permanent water inundation severely limits the soil productivity, curtails the farm incomes and drastically reduces the employment opportunities and thus considerably increases the rural distress. A study from the Western Yamuna and Bhakra canal commands in Haryana, India, found that irrigation-induced waterlogging and salinity drastically reduced the crop yields, leading to dismal farm incomes and decrease in farm employment (Singh and Singh 1995). In Tungabhadra irrigation project in Karnataka state, poor irrigation and drainage managements are responsible for large-scale land degradation. For the lower left bank main canal of the project alone, the economic loss due to soil degradation has been estimated to be about 14.5 % of the system's productive potential (Janmaat 2004). In Haryana state of India, the potential annual loss due to secondary salinity was estimated at Rs. 1669 million at 1998–1999 constant prices (Datta and De Jong 2002). The average annual losses due to waterlogging and salinity along the Lower Arkansas River of Colorado, USA, were estimated to be approximately US$ 4.3 million (Houk et al. 2006). Based on a review of previous estimates of salt-induced monetary losses, it was concluded that in financial terms, cumulative global crop loss was over US$ 27 billion (Qadir et al. 2014). Similar findings from other salinity-affected countries such as China (Khan et al. 2009), Egypt (Abdel-Dayem et al. 2007), Pakistan (Qureshi et al. 2008) and Bangladesh (Mirza 1998) show that besides extensive economic losses, salinity also adversely impacts infrastructure, water supplies and social stability (Pitman and Läuchli 2002). These examples show the widespread and historical shortcomings in irrigation development projects in developing countries where excess water applications and poor drainage accentuate the projected rates of soil degradation. Ultimately, persistent waterlogging and salinization greatly reduce the systems' potential than expected (Janmaat 2004).

3 The State of Groundwater Resources

Any discussion on secondary salinity and the related hazards must take into account the present state of groundwater use and management. It is because salinization in both dryland and irrigated regions is inextricably linked to groundwater dynamics. Again, as the success of salinity and sodicity reclamation programmes is largely based on the ample availability of good quality water, one must look into the emerging issues in water availability and use. Groundwater is an important and dependable source of water for agricultural, domestic and industrial sectors in India. Approximately 60 % of irrigated agriculture depends on groundwater wells which have been intensively exploited for maximizing the food grain production. Large-scale rural electrification, availability of electricity at cheaper rates and the schemes to expand the tube well-irrigated area have promoted unsustainable groundwater use resulting in rapid decrease in water table, waterlogging and salinization in irrigated lands. Intensive water extraction has also increased the pumping costs and has decreased the water quality as evident from high salt and pollutant loads and excess arsenic and fluoride levels in groundwater wells in different parts of the country (Singh and Singh 2002). Groundwater depletion at an alarming rate could wreck havoc to irrigated agriculture in northwestern part of India in the foreseeable future. A recent study based on satellite observations and simulated soil water variations revealed that annual groundwater loss has attained critical levels (~4 cm) in the states of Rajasthan, Punjab, Haryana and Delhi. This study suggests that effective measures such as reduction in water withdrawal are urgently required for arresting the rapid water decline to ensure stability in agricultural production and drinking water availability to the local residents (Rodell et al. 2009). The situation is particularly grim in many freshwater zones where fast receding water table (25–70 cm year^{-1}) in the last few decades has significantly increased the pumping costs and has decreased the water quality. Groundwater decline and the related problems can be overcome either by reducing the water withdrawal or by artificial groundwater recharge (Kumar et al. 2014). The importance of improved water management practices and efficient irrigation techniques in water saving has also been demonstrated (Ward and Pulido-Velazquez 2008). Given the compulsions to produce more food often with the aid of water-use inefficient irrigation practices, however, there is a limited scope for curtailing groundwater use in crop production, and the attempts to arrest the falling water tables through artificial recharge have gained currency. As a supplement to the natural recharge, simple artificial groundwater recharge techniques such as those based on recharge shaft and recharge cavity offer an attractive option to address this problem (Kumar et al. 2014).

Groundwater declines when water withdrawal exceeds the rate of natural replenishment as observed in intensively cultivated Indo-Gangetic plains of India. In Trans-Gangetic plains region comprising of Punjab and Haryana states, canal water allowance is very low, and it supplies about 150–200 mm of water to the rice-wheat cropping system (RWCS). Consequently, the farmers overly depend on saline groundwater to meet the crop water needs. The existing gap between actual water requirement (~1800 mm) and average annual rainfall (~600 mm) is responsible for the excess pumping of marginal quality groundwater and the consequent increase in soil salinity (Ambast et al. 2006). Fluoride (F^-) contamination of groundwater and the related health problems (e.g. dental and skeletal fluorosis) are gradually increasing in many parts of India (Jacks et al. 2005; Jha et al. 2013). High F^- water is not safe for human health, and about 62 million inhabitants in the states of Tamil Nadu, Andhra Pradesh, Gujarat, Madhya Pradesh, Punjab, Rajasthan, Bihar and Uttar Pradesh are at risk of F^- exposure. Although weathering of rocks is the main source of F^-, atmospheric depositions, industrial emissions and certain phosphorus fertilizers also contribute its small amounts to soil and water. Earlier considered to be a problem unique to the hard rock regions, F^- contamination is increasingly becoming an environmental issue in sodicity-affected irrigated lands (Jacks et al. 2005). Evidence is growing that areas having residual alkalinity ($Ca^{2+} < HCO_3^-$) in groundwater are particularly sensitive to F^- contamination. Evapotranspiration of groundwater having residual alkalinity lowers the Ca^{2+} level with a concurrent increase in Na/Ca ratio favourable to F^- build-up (Jacks et al. 2005; Jha et al. 2013). Keeping in mind the relation between sodic conditions and high-F^- groundwater, attempts have been made to study the effects of excess F^- in groundwater on crop growth and physiology so as to develop cost-effective solutions to mitigate this problem in the affected regions. Irrigation with F^--contaminated water increased F^- accumulation in grains of rice and wheat crops, and the concentration was found to be above safe limits for human consumption (Jha et al. 2013). The safe use of F^--contaminated water in non-edible economic crops such as *Populus deltoides* has also been suggested (Singh et al. 2013). Given the dwindling gypsum supplies, a set of surveillance and monitoring programmes coupled with efforts to explore the safe use of high-F^- water in non-edible crops seem to be a good option to alleviate this problem in sodic lands. The problem of high arsenic (>0.05 ppm), earlier endemic to West Bengal, is gradually increasing in many regions of India. High arsenic causes darkening and pigmentation of the skin and may lead to skin carcinoma (Chowdhury et al. 1999).

4 The Problem of Poor Quality Water

While freshwater reserves are declining at an alarming rate, the problem of poor quality water has also increased with the passage of time. As agriculture accounts for a major chunk of freshwater use, it becomes imperative to explore the strategies for optimizing cost-effective, environment-friendly and sustainable use of available water resources in crop production. Decrease in the availability of good quality irrigation water due to increasing population in urban areas and industrialization in many developing countries (Yadav et al. 2002) may aggravate in the future, and changing scenario would necessitate appropriate water management strategies, restricted irrigation and even the use of poor quality water for sustaining crop production (Oster 1994). Poor quality water (PQW), also referred to as marginal quality water, is a collective term for wastewater, saline and sodic water and agricultural drainage water. In many regions of the world, farmers irrigate their crops with untreated wastewater (domestic and industrial effluent) with potential environmental and health risks as untreated wastewater often carries injurious heavy metals, metalloids, pathogens and residual drugs. Contrary to wastewater, saline and sodic water contains toxic salts that suppress the plant growth and cause heavy reductions in crop yield. Continuous use of saline and sodic water may also cause waterlogging and secondary salinization (Qadir et al. 2007). Inadequate availability of good quality water and the lack of wastewater treatment facilities are the reasons which compel many farmers to use untreated wastewater in irrigation (Qadir et al. 2007). Similarly, two factors—predominance of saline aquifers in arid and semiarid zones and increasing competition between agriculture and other sectors for freshwater use—compel the farmers to use saline and sodic water in agricultural production (Shannon and Grieve 2000). This is the case in (semi)arid northwestern India, where in many cases saline groundwater is the only viable option available to the farmers. In such regions, saline, sodic and saline-sodic water constitute about 20, 37 and 43 %, respectively, of the total poor quality groundwater. As good quality canal water is available in limited amounts, farmers use a blend of saline water and canal water to irrigate the crops which comes with yield penalty and causes salt accumulation in soil (Kaledhonkar et al. 2012).

Precise estimates are not available regarding the extent of wastewater use in arable crops. In most of the cases, either untreated or partially treated wastewater is used in vegetables and some other horticultural crops by the small and marginal farmers in the peri-urban regions (Qadir et al. 2007). In many parts of the world, however, treated wastewater is also used (Zekri and Koo 1993). Long-term applications of treated wastewater did not cause any appreciable reduction in tree growth and fruit yield in citrus, and wastewater reuse required only minor adjustments in crop management practices (Morgan et al. 2008). Drip irrigation with treated municipal water was found safe in olive trees which produced fruits of acceptable hygiene. Soil properties in the top 10 cm soil were only seasonally affected as specific soil, and irrigation management practices excluded water percolation and avoided transport of exogenous bacteria to the deeper soil layers (Palese et al. 2009). In tomato, wastewater application did not cause any significant reduction in fruit yield and quality, and harvested fruits exhibited heavy metal concentrations below the permissible limit (Al-Lahham et al. 2007). A few reports on the use of untreated wastewater in horticultural crops are also available. Studies conducted in olive (Murillo et al. 2000) and different vegetable crops (Brar et al. 2000; Melloul et al. 2001; Kiziloglu et al. 2008) showed that untreated wastewater application would not be a safe option in longer runs. In potato, for example, irrigation with untreated sewage effluent significantly increased concentrations of Fe, Mn, Zn, Al and Ni up to 60 cm and that of Cu and Cr up to 30 cm soil depth. It also increased the concentrations of these elements in potato leaves and tubers (Brar et al. 2000).

The factors instrumental in promoting wastewater use in agriculture, especially in arid and Mediterranean climates of both industrialized and developing countries, include freshwater scarcity, growing recognition of the importance of wastewater reuse, high costs of artificial fertilizers and the sociocultural acceptance of this practice (Mara and Cairncross 1989). Being a rich source of many essential crop nutrients, the effects of treated wastewater use may be similar to that of frequent fertigation with dilute nutrient concentrations (Maurer and Davies 1993). Water-stressed countries such as Israel and the USA (mainly the states of Florida, California and Arizona) are leaders in wastewater reuse practices (Angelakis et al. 1999). Treated wastewater is likely to be the major (~70 %) source of water for irrigation in Israel by 2040 (Palese et al. 2009). Still some other countries like Cyprus, Jordan and Tunisia have also made remarkable progress in treated wastewater use in irrigation. In these countries, where immense value of reclaimed wastewater use is fully recognized, elaborate regulations and safety standards have been put in place to ensure the environmentally safe reuse of wastewater (Angelakis et al. 1999).

In many irrigated regions of the world, marginal quality drainage water is regularly used in irrigation adding dissolved salts to the soils (Fayrap and Koc 2012). In surface irrigated soils, heavy irrigation even with good quality water will add substantial amounts of salt to the soil. For example, application of about 1900 mm fresh canal water (EC_{IW} 0.3 dS m^{-1}) will add about 3.7 t ha^{-1} of salts to the soil profile (Ritzema et al. 2008). Groundwater in many parts of southwestern Punjab contains excessive amounts of dissolved salts and residual sodium carbonate (RSC). Irrigation water salinity ranges from 2 to 7 dS m^{-1}, and RSC is generally greater than 10 me l^{-1} up to 10 m depth (Shakya and Singh 2010). Although SSD has proved highly successful in ameliorating the waterlogged saline lands, it generates huge volumes of saline drainage water creating formidable problems in its safe disposal. This condition has prompted increasing interest in using the saline water, in conjunction with fresh water, in irrigation. Although potential uses of saline drainage water in crop production are well recognized, many issues need to be addressed to give it a wide acceptability (Sharma and Rao 1998). The use of sodic water having residual sodium carbonate in the range of 5–7 m mol L^{-1} has been considered safe for wheat-fallow rotation in moderately coarse soils. It is based on the premise that while irrigation in wheat crop would enhance the sodicity, rains in the ensuing monsoon months would favour the salt leaching (Kaledhonkar et al. 2012). Sustained use of saline and sodic drainage waters in irrigation requires the use of salt-tolerant crops, appropriate leaching to avoid deterioration of soil physical conditions and the use of amendments such as gypsum (Oster and Grattan 2002).

5 Plant Growth and Physiology in Salt-Affected Soils

Salt-affected soils (SAS) comprise of saline and sodic soils which differ in origin, physico-chemical properties and the constraints to plant growth. Due to presence of excess soluble salts (e.g. chlorides and sulphates of Na^{+}, Ca^{2+} and Mg^{2+}), saline soils exhibit saturation extract electrical conductivity (EC_e) values ≥4 dS m^{-1}. The major limitations to plant growth in saline soils include osmotic stress (i.e. physiological drought) and specific ion toxicities. The sodic soils, on the contrary, have high exchangeable sodium percentage (ESP; >15) which adversely affects water and air flux, water-holding capacity, root penetration and seedling emergence. At high ESP, the clay particles disperse resulting in poor aggregate stability and impeded drainage (Munns 2005). The cell-specific events which affect key metabolic pathways and cause injury in salt-stressed plants include cell membrane damage due to electrolyte leakage and lipid peroxidation, oxidative stress caused by the free oxygen radicals, impaired leaf water relations, altered gas exchange characteristics and ion toxicities. Depending on factors such as salt concentration, crop species and growth stage, these impairments adversely affect cell physiology and functioning leading to the appearance of damage symptoms, stunted growth and yield reduction in salinized plants.

Electrolyte leakage (EL) and lipid peroxidation (LP) are two common indicators of cell membrane damage in plants under stress conditions. Considering the fact that adverse growing conditions damage the cell membranes leading to leakage of solutes into the apoplastic water, measurement of EL may provide a good estimate of salt-induced cell injury (Lindén et al. 2000). Malondialdehyde (MDA) level, a product of lipid peroxidation in plants exposed to adverse environmental conditions, is frequently used to assess the degree of salinity-induced free radical generation and oxidative damage to cell membranes (Najafian et al. 2008). As the extents of EL, LP and MDA production vary in salt-treated plants, these parameters have been widely studied to estimate the oxidative stress and cell membrane stability so as to differentiate the salt-tolerant lines from the salt-sensitive ones. Salt stress alters the integrity and permeability of cell membranes causing excessive electrolyte leakage from the cell. It has been shown that Na^+ and Cl^- ions coupled with oxidative stress cause lipid peroxidation and increase the permeability of plasma membranes in salinized plants (Mansour 2013). In salt-stressed plants, Na^+ displaces Ca^{2+} ions involved in pectin-associated cross-linking and plasma membrane binding leading to membrane damage (Essah et al. 2003). Specific membrane proteins and/or lipids, either constitutive or induced, as well as compounds such as glycinebetaine, proline and polyamines may contribute to cell membrane stability in salt-tolerant genotypes (Mansour 2013).

Although normally produced during plant metabolism, stress conditions induce rapid generation of harmful active oxygen species (AOS), also referred to as reactive oxygen species (ROS), such as superoxide radicals (O_2^-), singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2) and hydroxyl radical (OH) in plant cells (Misra and Gupta 2006). Under stress conditions, the ability of plants to scavenge AOS is greatly reduced causing free radical levels to exceed the critical threshold. Accumulation of AOS and their interaction with biomolecules often impairs cell structure and functioning (Kochhar et al. 2003). Given their 'highly reactive' nature, the AOS disrupt cellular function by causing oxidative damage to cell membranes and organelles, vital enzymes, photosynthetic pigments and biomolecules such as lipids, proteins and nucleic acids. To overcome the potential damage, plants synthesize diverse antioxidant compounds for the detoxification and removal of the deleterious free radicals with the degree of protection depending on factors such as species/cultivar, growth stage and the type and duration of stress.

Most of the higher plants tend to decrease the leaf water potential (Ψ_w) and leaf osmotic potential (Ψ_S) with consequent changes in leaf turgor potential (Ψ_P) under saline conditions (Chartzoulakis 2005). Increasing salinity in root zone almost invariably decreases the leaf chlorophyll concentration with the extent of decrease depending on salt concentration, genotype and growth stage. Under certain conditions, however, salt-tolerant genotypes may exhibit marginal increase in leaf chlorophyll relative to control plants. Chlorophyll is a membrane-bound pigment, and its integrity depends on membrane stability. As cell membranes are damaged under saline conditions, chlorophyll seldom remains intact. Again, salt-induced increase in chlorophyllase activity and accumulation of Na^+ and Cl^- ions in the leaves accentuate the rate of chlorophyll degradation (Ali-Dinar et al. 1999; Singh et al. 2015). Decrease in photosynthesis under saline conditions is attributed to diverse limitations ranging from restricted CO_2 supply to chloroplast cells caused by stomatal resistance and reduced CO_2 transport in mesophyll cells caused by cell membrane leakage, leaf shrinkage-induced alterations in the structure of intercellular spaces and biochemical regulations. Impaired carbon assimilation in salt-stressed plants may also be due to excessive concentrations of Na and Cl in the leaf tissue (in general above 250 mM) (Munns et al. 2006). The degree of photosynthetic recovery in salt-stressed plants depends on the magnitude and duration of salt treatment. In general, plants subjected to mild stress show fast recovery (within 1 or 2 d) after stress is relieved, but plants subjected to severe stress recover only 40–60 % of the maximum photosynthetic rate after stress is alleviated (Chaves et al. 2009).

The two-phase inhibition of plant growth in saline soils, which involves an initial osmotic shock followed by ion injuries, differs with the crop. In annual plants, salt-induced toxicity symptoms generally develop within few days, while in perennial crops salt injury may become noticeable after months or even years. It has been shown that while osmotic stress equally affects both tolerant and sensitive genotypes, specific salt effects mainly hamper the growth in sensitive lines (Munns 2005). The perennial fruit trees differ from the annual field crops in many respects when grown in saline soils. Contrary to the annuals which generally exhibit higher salt tolerance with age, most of the fruit crops tend to become salt sensitive as they grow older. It is attributed to carry over of salts stored in roots to leaves as well as slower growth rates in older plants. Again, highly salt-sensitive species such as citrus and stone fruits tend to accumulate Na^+ to toxic levels in soils which are essentially normal. Under certain conditions, Na^+ and Cl^- may not be the predominant ions in saline soils, and the use of rootstocks that restrict the uptake of these toxic ions may render specific salt effects relatively unimportant, and osmotic inhibition will thus virtually cause most of the deleterious effects in salinized fruit plants (Bernstein 1980).

6 Mechanisms of Salt Stress Alleviation

Unlike the animals, Na^+ is not essential for plants except in halophytes where Na^+ accumulation in cell vacuoles is implicated in osmotic adjustment. Animal cells respond to high extracellular salt concentrations through plasma membrane Na^+/K^+-ATPase channel-mediated Na^+ efflux and K^+ influx to establish a K^+/Na^+ ratio favourable to cell functioning. Plant cell membranes, in contrast, possess H^+-ATPase which creates H^+ electrochemical gradient for regulating the ion transport and uptake. As hydrated Na^+ and K^+ ions have a similar radius, K^+ transport channels in plants fail to distinguish between the two, and the resultant higher Na^+ influx alters the ionic balance and adversely affects a myriad of cellular processes. It has been shown that Na^+ concentrations above 100 mM induce a sharp reduction in cell K^+ levels which in turn affects the protein synthesis. It is interesting to note that many important cytosolic enzymes in both salt-tolerant halophytes and salt-sensitive glycophytes are equally sensitive to high salt concentrations (Blumwald 2000). Salt-stressed plants alleviate Na^+ toxicity either by excluding the excess Na^+ or by sequestering it in the vacuoles. After vacuoles become saturated, Na^+ ions flow to the cytosol and apoplast and affect the enzyme activities and cell turgor, respectively. Thus, both salt exclusion by the roots and Na^+ accumulation in vacuoles are the traits that confer salt tolerance to the plants (Rausch et al. 1996).

Accumulation of free radicals in salinized plants enhances the activity of antioxidant molecules. The main antioxidant enzyme is superoxide dismutase (SOD). It is a metalloprotein that catalyzes the conversion of superoxide radical into hydrogen peroxide. There are several SOD isozymes: Mn-SOD, Cu/Zn-SOD and Fe-SOD. To avoid hydrogen peroxide accumulation, a compound even more damaging than superoxide radical, enzymes catalase (CAT) and ascorbate peroxidase (APX) are activated (Arbona et al. 2003). Salt-stressed plants tend to accumulate proline for overcoming the osmotic stress and cellular dehydration. The stress protection activities of proline are attributed to its involvement in osmotic adjustment, stabilization of subcellular structures and the elimination of free radicals (Hare and Cress 1997). In halophytes, proline is the major component of amino acid pool under salt stress. While proline levels remain low under nonsaline conditions, salinized plants show manifold increase in proline concentration (Stewart and Lee 1974). The increase in proline content is mostly positively correlated with the level of salt tolerance, and salt-tolerant genotypes generally show elevated proline concentrations as compared to salt-sensitive ones (Ghoulam et al. 2002). Plants facing Na^+-induced cellular toxicity tend to maintain the osmotic water balance by lowering the leaf water potential below that of soil water so as to ensure smooth water uptake for the turgor maintenance. Osmotic balance can be achieved either by solute uptake from the soil or alternatively by synthesizing compatible solutes such as proline and sugars. From an energy-use point of view, uptake and accumulation of inorganic ions such as Na^+ and Cl^- is a cheap option but with inherent danger of cellular toxicity. In contrast, osmotic adjustment though compatible organic compounds is a safe but energy-intensive strategy (Tester and Davenport 2003).

7 Salinity-Environment Interaction

Different environmental factors including temperature, humidity, light intensity and CO_2 concentration influence the crop response under saline conditions. In majority of the cases, crops exhibit greater salt tolerance when grown in cool and humid locations. The hot and dry conditions, in contrast, increase the salt stress (Francois and Maas 1994). Even subtle changes in atmospheric temperature and humidity, due to anticipated climate change, may adversely affect growth and development in crop grown in saline soils (Yeo 1998). Although it is generally agreed that prevailing weather conditions determine plant response to salinity, the non-specific nature of most of the environmental variables makes it difficult to quantify their effects on plants growing in saline media. Atmospheric temperature, however, is perhaps the least specific of all the environmental factors as it affects a range of soil and plant processes including salt dynamics in the soil and transpiration and mineral nutrition in plants that are important in relation to salinity (Gale 1975). Seed germination in *Crambe* (*Crambe abyssinica* Hochst. ex R.E. Fries), a potential oilseed crop for saline soils, was severely affected at 5 °C even in control treatments. Better germination in salt-treated plants (6.3–36.3 dS m^{-1}) was recorded at temperature range of 15–25 °C, germination peaked at 20 °C and decreased at both low (10 °C) and high (30 °C) temperature regimes (Fowler 1991). The highest seed germination and better seedling growth in salinized (516 mM NaCl) *Atriplex griffithii* var. *stocksii* plants were observed at cooler alternating temperature (25:10 °C) and inhibited at warmer (30:15, 30:20 and 35:25 °C) regimes (Khan and Rizvi 1994). In sorghum (*Sorghum* *bicolor* L.), salinity (6.4–37.2 dS m^{-1}) decreased the germination percentage, but effects were less severe at higher (30–40 °C) than lower (15–25 °C) temperatures (Esechie 1994). Safflower (*Carthamus tinctorius*) plants grown under different osmotic potentials (−0.3 to −0.9 MPa) and three constant temperatures (15, 25 and 35 °C) showed higher growth at 25 °C as compared to other (15 and 35 °C) temperature levels (Gadallah 1996).

Barley, wheat and sweet corn grown under nonsaline and saline media showed differential response to the low (45 %) and high (90 %) relative humidity (RH) treatments. High RH enhanced the salt tolerance of barley and corn but had no effect on wheat. For all the three crops, water-use efficiency was higher at 90 % than at 45 % RH at different osmotic potentials (Hoffman and Jobes 1978). High RH (90 %) alleviated salt stress in onion and radish but not in beet (Hoffman and Rawlins 1971). Salt-induced growth reduction in bean plants occurred at both low and high RH levels. However, high RH conditions favoured better growth in salinized plants as compared to salt-treated plants grown under low humidity (Prisco and O'Leary 1973). It was found that high humidity conditions markedly alleviated salt stress in both cotton and bean but the effects were more pronounced in cotton as compared to bean (Nieman and Poulson 1967). These observations indicate that high humidity enables better growth in salt-stressed plants by improving the transpiration rate for sustained water and nutrient uptake (Nieman and Poulson 1967). Light irradiance also affects the growth in salinized plants. Higher reduction in growth is likely at high than low light conditions for equivalent salinities (Francois and Maas 1994). Salinized plants of strawberry cultivar 'Rapella' produced fruits with lower dry matter concentration when grown at low irradiance (2.1 MJ m^{-2} day^{-1}) in comparison to those grown under unshaded condition (4.9 MJ m^{-2} day^{-1}). Lower concentrations of reducing sugars in the shaded and salinized plants was attributed to salinity-induced reduction in carbon partitioning into sucrose and its restricted translocation from leaves to the fruits (Awang and Atherton 1995). The use of shade screens increased water- and radiation-use efficiencies as well as the quality of tomato fruits irrigated with saline solutions (EC_{IW} 3.1 and 5.1 dS m^{-1}). Marketable fruit yield (12.1 kg m^{-2}) under shaded 3.1 dS m^{-1} treatment was significantly higher than control plots (11.1 kg m^{-2}) greenhouse. The incidence of blossom-end rot was also remarkably lower in the shaded treatments under both salinity levels (Lorenzo et al. 2003). Spring tomato crop was grown under different climatic conditions and salinity (1.7–6.4 dS m^{-1}) levels. Under poor light conditions, high salinity usually did not adversely affect long-term production (Sonneveld and Welles 1988).

Atmospheric CO_2 concentration has increased from 270 μmol mol^{-1} in the pre-industrial era to 389 μmol mol^{-1} in 2010, and further increase is imminent due to rising use of fossil fuels. The net carbon assimilation in plants increases with increase in atmospheric CO_2 concentration resulting in an enhanced net primary production. This CO_2-fertilization effect is more pronounced in C_3 plants where photosynthesis is CO_2 limited (Lenka and Lal 2012). Most of the halophytes exhibit high water-use efficiencies under salt stress. Increase in CO_2 concentration further reduces the water loss and increases the growth resulting in even higher water-use efficiency. In spite of substantial differences in WUE, plants grown at equivalent salinities and different (normal and elevated) CO_2 levels do not exhibit differences in leaf salt concentration, indicating that salt uptake is not linked to water use (Ball and Munns 1992). Salt-stressed plants of *Phaseolus vulgaris* and *Xanthium strumarium* (both C_3 species), *Zea mays* (salt-sensitive C_4 plant) and *Atriplex halimus* (C_4 halophyte) exhibited significant increase in plant dry weight under high (~2500 μl I^{-1}) CO_2 conditions (Schwarz and Gale 1984). The interactive effect of CO_2 and NaCl on the second trifoliate leaf of *Phaseolus vulgaris* L. showed that elevated CO_2 partially overcame some salinity effects such as leaf area, volume, specific leaf area and relative leaf expansion rate (Bray and Reid 2002). Saline irrigation (150 mol m^{-3} NaCl) greatly reduced tillering in both *aestivum* and *durum* wheat cultivars. High CO_2 partly reversed the effects of salinity as evident from significantly high dry matter accumulation under salt treatment (Nicolas et al. 1993). Saline irrigation (0, 25, 50, 75, 100 % seawater salinity) in halophyte *Aster tripolium* increased the stomatal and mesophyll resistance causing a significant decrease in photosynthesis and water-use efficiency and higher oxidative stress as indicated by dilations of the thylakoid membranes and an increase in superoxide dismutase (SOD) activity. Under these conditions, elevated CO_2 (520 ppm) mitigated salt stress and significantly improved photosynthesis and water-use efficiency (Geissler et al. 2009). Higher growth due to improved water-use efficiency, however, may alter the soil-plant-water balance and could cause a rise in water table bringing the dissolved salts to the surface (Munns et al. 1999).

Salinity-ozone interaction studies have revealed that higher ozone concentration may either have no effect or may accentuate the effects of salinity. Garden beets (*Beta vulgaris* L.) grown in saline nutrient solution cultures having osmotic potentials of −0.4, −4.4 and −8.4 bars, respectively, were exposed for 5 weeks to 0.20 ppm ozone for 0–3 h/day. Development of foliar ozone injury symptoms in salt-treated plants was rather slow, and both shoot and root growth were relatively unaffected by ozone exposures of up to 3 h/day^{-1} (Ogata and Maas 1973). Bean (*Phaseolus vulgaris* L.) plants were grown under osmotic potentials of −0.4, −2.0 and −4.0 bars and were exposed to 0, 0.15, 0.25 and 0.35 ppm of ozone. The results indicated no interaction between salinity and ozone below 0.15 ppm (Hoffman et al. 1973). In nonsalinized alfalfa (*Medicago sativa* L. cv. Moapa) plants, ozone at 10, 15 and 20 parts per hundred million (pphm) reduced the forage yield by 16, 26 and 39 %, respectively. As salinity increased, ozone had less effect on yield. Alfalfa exposed to 20 pphm of ozone for 2 h daily yielded 25 % more at −200 kPa osmotic potential than control (−40 kPa) plants (Hoffman et al. 1975). Rice (*Oryza sativa* L.) varieties differing in salt tolerance were grown under saline conditions with or without a repeated exposure to ozone at a concentration of 83 nmol mol^{-1}. Both salinity and ozone reduced the plant height, leaf K^+ concentration, gas exchange and CO_2 assimilation. Ozone reduced the leaf Na^+ concentration at 50 mm NaCl but had no effect upon Cl^- concentration (Welfare et al. 1996). Salinity (30 mM NaCl) considerably reduced the plant height, number of leaves and dry weights of the leaves, stems and roots. Exposure to 85 nmol mol^{-1} ozone for 6 h per day caused further growth reduction in salt-stressed plants (Welfare et al. 2002).

8 Mapping and Characterization of Salt-Affected Soils

Considering the fact that accurate delineation of salt-affected lands is one of the prerequisites for their productive utilization, concerted efforts have been made to develop updated salinity maps for different states of India. The availability of many cost-effective and robust techniques such as geographic information system and remote sensing has considerably expedited the progress in characterization of saline and sodic soils. Remote sensing, often in combination with ground truth observations, provides speedy and accurate information on distribution and extent of SAS (Singh et al. 2010). Using appropriate models, multispectral high-resolution satellite imageries are processed into thematic maps to assess the spatial and temporal variability in salinity and alkalinity (Farifteh et al. 2006). Till date, mapping on 1:250,000 scale has been done in 15 salt-affected states, and the efforts are in progress to digitize the maps on 1:50,000 scale. By reconciling different estimates, the total salt-affected area in the country has been computed to be 6.73 million ha. Saline and sodic soils constitute about 40 % and 60 %, respectively, of the total salt-affected soils. Availability of information regarding state-wise distribution of saline and sodic soils (Table 1) has proved helpful in planning and executing the soil reclamation programmes (Singh et al. 2010). In addition, the first approximation water quality map of India has also been published (Sharma and Singh 2015).

The traditional approach of salinity mapping is based on intensive soil sampling and the subsequent laboratory analyses to determine soil pH, electrical conductivity and other chemical properties. However, as these methods are costly and time-consuming

Table 1 Statewise distribution of salt-affected soils in India (ha)

State	Saline soils	Sodic soils	Total
Andhra Pradesh	77,598	196,609	274,207
Andaman and Nicobar Islands	77,000	0	77,000
Bihar	47,301	105,852	153,153
Gujarat	1,680,570	541,430	2,222,000
Haryana	49,157	183,399	232,556
Karnataka	1893	148,136	150,029
Kerala	20,000	0	20,000
Madhya Pradesh	0	139,720	139,720
Maharashtra	184,089	422,670	606,759
Orissa	147,138	0	147,138
Punjab	0	151,717	151,717
Rajasthan	195,571	179,371	374,942
Tamil Nadu	13,231	354,784	368,015
Uttar Pradesh	21,989	1,346,971	1,368,960
West Bengal	441,272	0	441,272
Total	2,956,809	3,770,659	6,727,468

Source: NRSA and Associates 1996

(Allbed and Kumar 2013; McNeill 1992), rapid, efficient and practically feasible tools are required to assess the spatial-temporal variations in salinity in crop fields (Wiegand et al. 1994). To overcome the limitations associated with conventional methods, initially in situ direct current resistivity technique was tried with limited success due to slow speed of the resistivity measurements (McNeill 1992). Over the years, the idea that apparent soil electrical conductivity (EC_a) measurements could provide a reasonable estimate of EC_e-gained currency and EC_a measurements increasingly came into use. Electromagnetic (EM) induction, electrical resistivity and time-domain reflectometry (TDR) techniques are used to measure EC_a which is influenced by different soil properties including the soluble salt, clay and water contents, soil bulk density, organic matter and soil temperature. Given that EC_e is the standard measure of salinity, the EC_a values are converted into EC_e by non-linear and linear transformations (Corwin and Lesch 2005). The commonly available EM probes such as EM-31 and EM-38 (Corwin and Lesch 2005) send electromagnetic currents in the ground to measure the magnetic field strength to determine the soil conductivity. EM techniques are better suited to 'conductive' soils having high salt concentrations. The spacing between the transmitter and receiver coils determines the effective depth up to which EM devices can predict the salinity (McNeill 1992). In some cases, EC_e may show low correlation with EC_a due to sample-size differences, but the calculated EC_a values often accurately predict whether the measured EC_e would lie above or below some threshold value (Sheets et al. 1994). TDR technique is also employed for the simultaneous determination of soil water content and salinity (Dalton 1992) particularly in light soils with low conductivity as in heavy-textured (e.g. clay) soils surface conduction weakens the force of TDR signal (Zegelin et al. 1992). In situ TDR measurements give results comparable with those obtained by conventional non-destructive techniques (Dalton and Van Genuchten 1986).

Advent of different sensor-based techniques such as aerial photography and videography, satellite- and airborne-multispectral sensing, hyper-spectral imaging and remote sensing have considerably enhanced the speed and accuracy of salinity mapping (Metternicht and Zinck 2003). Remotely sensed multispectral satellite data on salt reflectance at the soil surface are processed using techniques such as spectral unmixing, maximum likelihood classification, fuzzy classification, principal components analysis and correlation equations to yield the valid inferences. The main limitations to the use of remote sensing in the characterization of salt-affected soils include the changes in spectral reflectance characteristics of salts, spatial-temporal variations in salt concentration, interference of vegetation and the spectral confusions with other terrain surfaces (Metternicht and Zinck 2003). Of late, frontier technology-driven tools are increasingly being applied for salinity mapping and generating informative resource inventories in a short span of time. Besides broadening the existing understanding of major limitations to plant growth, these techniques have opened new avenues for the precision farming and site-specific management in salt-affected lands. Advances in computer modelling and geostatistical techniques have made it possible to characterize the spatial variability of soil chemical properties so as to identify productive crop management zones in a given saline tract (Li et al. 2007). Integrated hydro-geochemical and geophysical methods are also increasingly proving useful in assessing the extent groundwater salinity. Different hydro-geochemical parameters (e.g. ion content, pH and total dissolved salts) of the groundwater along with geophysical tools (geoelectrical resistivity soundings and reflection seismic surveys) are used to estimate the water quality in saline aquifers. These techniques not only provide the precise estimates of salinity and ionic composition in groundwater, but they also reveal potential zones of fresh- and saltwater interface for the future water management plans (Samsudin et al. 2008). A combination of aircraft surveys and in situ measurements was employed to map the surface and subsurface salinity distributions, respectively, in the Great Barrier Reef Lagoon. While airborne sensors provided rapid assessments of the spatial extent of the surface salinity, in situ measurements revealed the subsurface salinity status in detail (Burrage et al. 2003).

9 Technologies for Harnessing the Productivity of Saline Lands

Globally, about 25 % (~3.2 billion hectares) of the total land area is used as arable land, i.e. land under temporary crops and pastures, market or kitchen gardens and the fallow land. The agricultural land (arable land area under permanent crops and pastures) constitutes about 40–50 % of the total global land. Sustainable soil health is of paramount importance to the survival and development of human society. These soil functions and services have become more important than ever in face of challenges such as climate change, water and energy scarcity and biodiversity loss. A precise estimate of crop and monetary losses due to salinity is very difficult. Nonetheless, it is important to note that current losses attributed to salinization are huge with at least 20 % of the global irrigated lands suffering from production losses to varying degrees (Pitman and Läuchli 2002). It is increasingly being realized that technology-led productivity enhancements in salinity-affected regions would greatly relieve the pressure on prime agricultural lands. Even modest productivity gains will significantly improve the rural livelihoods in most of the resource poor and harsh arid environments suffering from the problems of soil and water salinity. A brief account of salinity management technologies and the constraints in their use are discussed under the following heads:

9.1 Improving the Land Drainage

Although reliable estimates are not available, twin problems of waterlogging and salinity are responsible for the massive reduction in food grain production in many parts of the world. In northwestern India, especially in parts of Haryana and Punjab states, over 1 m ha agricultural lands are affected by these problems. Beginning with some pilot drainage projects in Haryana in the 1980s, the ICAR-Central Soil Salinity Research Institute, Karnal, spearheaded the efforts in this direction, and it soon became evident that subsurface drainage (SSD) is a viable technology for restoring the productivity of such lands (Datta et al. 2004). Over the years, significant improvements in the design and drain spacing have considerably enhanced the adoption of SSD. The SSD network consists of a network of concrete or polyvinyl chloride (PVC) pipes along with filters installed manually or mechanically at a specified spacing and depth below the soil surface. Initially developed for Haryana, SSD projects have been successfully implemented in Rajasthan, Gujarat, Punjab, Andhra Pradesh, Maharashtra, Madhya Pradesh and Karnataka states (Gupta 2002, 2015). The reclaimed soils show significant improvements in soil properties and give considerably higher crop yields. In spite of tangible gains such as higher incomes to the land owners, generation of farm employment and improvements in environmental quality, both implementation and the maintenance of SSD projects face many socio-economic constraints. While higher initial costs restrict the implementation in many cases, prohibitive maintenance costs and the lack of community participation are responsible for project failures at majority of the sites. This state of affairs underscores the importance of active community involvement as a key to the success of SSD projects (Ritzema et al. 2008). In light of defunct or weak community management due to disparity in benefits from drainage, differences in the socio-economic backgrounds of the members and conflict of interest between head- and tailenders, a co-operative institutional set-up has also been suggested (Datta and Joshi 1993). Besides these socio-economic constraints, disposal of saline drainage effluents is another limiting factor especially in the landlocked locations. A number of strategies such as the use of evaporation ponds (Tripathi et al. 2008), blended or cyclic use of saline and fresh (Datta et al. 1998) and the use of salt-tolerant cultivars (Sharma and Rao 1998) are suggested for enhancing the acceptability of this technology at farmers' fields.

Impeded drainage in coastal lands is due to heavy and concentrated downpour, flat land topography, poor water infiltration and the lack of well-defined drainage systems. In poorly drained lands, continuous use of even marginally saline water (2 dS m^{-1}) causes salt accumulation (Yadav et al. 1979). Heavy-textured soils in low-lying zones are particularly sensitive to waterlogging. The presence of excess amounts of insoluble humic acid in coastal soils of West Bengal adversely affects their water permeability. These soils also exhibit poor sorptivity characteristics which significantly reduced their ability to absorb the water during infiltration. Deep tillage, addition of sand and vertical drainage may enhance hydraulic conductivity in these soils (Raut et al. 2014). In low-lying heavy soils having poor hydraulic conductivity, surface drainage to remove the excess water suffers from the lack of natural outlets and backwater flow (Ambast et al. 2007). A few preliminary studies conducted in the decades of the 1960s and 1970s provided useful insights for the reclamation of coastal saline soils by subsurface drainage. The results obtained with respect to the method, depth and duration of ponding and the type of drains to be used encouraged further attempts in this direction. In soils having very poor hydraulic conductance (2–10 cm day^{-1}) in the upper 1.5 m profile, drain spacing of 15 m with a depth of 1.75 m and a length of 35 m gave the best results in combination with water ponding (Yadav et al. 1979). In heavy-textured coastal saline-sodic soils, closer drain spacing (15 m) proved more effective as compared to wider spacings in terms of rice grain yield. Considerably lower rice yields obtained with wide drain spacings (35 and 55 m) were attributed to the heavy loss of ammonium form of nitrogen through the drainage effluent resulting in limited availability of total nitrogen to the plants (Singh et al. 2001). Limited practical utility of surface and subsurface drainage interventions in coastal soils, however, has generated interest in other techniques for salt leaching by improving the physical properties and hydraulic conductivity. For example, sand application at the rate of 30 % by volume and soil mulching with rice husk (10 t ha^{-1}) significantly improved the water flux leading to salt displacement to the lower profiles. Round-the-year rice cultivation with good quality water (EC_{iw} ~1.5 dS m^{-1}) has also been found effective in reducing the salt content in the soil apparently due to salt leaching due to continuous ponding of water (ICAR-CSSRI 2015).

9.2 Land Shaping Models

It has been shown that landscape characteristics affect the soil water flow, soil development and soil change and are linked to land degradation. An understanding of the interplay between these processes may be of great help in developing appropriate and efficient management strategies to arrest the land degradation (Fritsch and Fitzpatrick 1994). Soils having better water permeability are amenable to land-use intensification through simple agronomic practices such as early crop sowing, replacement of less productive land races with high-yielding cultivars and integration of crop and high value components. Multiple cropping and increase in crop yields literally translate into enhanced availability of food, feed and energy from the same land unit. A combination of crops and other components increases the availability of diverse food resources to the farm families (Saleem and Astatke 1996). The usefulness of a few simple and economically viable land shaping techniques including farm ponds and paddy-cum-fish model for enhancing the productivity of degraded waterlogged saline lands has been demonstrated (Ambast et al. 1998). Soils having poor water permeability often suffer from the problems of water inundation and salinity. Rainwater harvesting in such man-made structures serves twin purposes of salinity mitigation and enhanced availability of irrigation water during the dry season. Establishment of the farm ponds involves the excavation of about 20 % of the farm soil from a depth of about 3 m. The excess rainwater is harvested in these ponds for irrigating the crops grown on embankments round the year. In addition to fish rearing in the pond and crop production on dykes, there are ample prospects for integrating other components such as poultry and duckery to further enhance the land value while promoting the resource conservation and recycling among the different components. In paddy-cum-fish model, trenches (3 m top width × 1.5 m bottom width × 1.5 m depth) are dug around the periphery of the farmland leaving about 3.5 m wide outer from boundary, and the dugout soil is used for making dikes (about 1.5 m top width × 1.5 m height × 3 m bottom width) to protect free flow of water from the field and harvesting more rainwater in the field and trench. While dykes are used to grow vegetables throughout the year, the remainder of the farmland including the trenches is used for integrated rice-fish culture (Mandal et al. 2013). Severe waterlogging is one of the major constraints in productive utilization of vertisols in Ethiopian highlands. The conventional surface drainage approach to overcome this problem has not given desirable results, and accordingly focus has shifted to alternative technologies for improving the crop yields. These approaches including broad bed and furrows (BBF) and ridge and furrows (RF), often in combination with green manuring and reduced tillage, have improved land quality and crop yields at many locations (Abebe et al. 1994; Erkossa et al. 2004; Erkossa et al. 2006) mainly by enhancing the drainage. The extent of drainage effect on crop yields was dependent on rainfall quantity, clay content and crop species (Abebe et al. 1994). Many economically viable land shaping technologies have become successful in coastal saline tracts of the country, and efforts are in progress to demonstrate their utility under waterlogged saline and sodic conditions in inland regions of the country (Sharma and Chaudhari 2012).

9.3 Techniques for Groundwater Recharge

Different simple practices of groundwater recharge in water-stressed northwestern parts of India have been discussed by Kaushal (2009). These include rooftop rainwater harvesting, recharge through recharge wells, village ponds and surface drainage network and water conservation in rice fields. Rooftop rainwater harvesting arrests the soil erosion, reduces the flood hazard and improves the groundwater quality. The use of recharge wells to capture the surface runoff, rehabilitation of village ponds to provide irrigation and recharge underground aquifers and utilizing the vast drainage network constructed for flood control also significantly improve the groundwater resources. Rainwater conservation in paddy fields to control the declining water table by reducing the groundwater draft and enhancing the groundwater recharge should also be given focus. Again, enactment of appropriate legislations at national and state levels to prevent indiscriminate exploitation of the water resources is urgently required. Groundwater in the rice-wheat sequence in the Trans-Gangetic plains of India is either fresh or marginally saline. While tube well density is high (15 km^{-2}) in most of the freshwater zones, it is considerably low in the poor quality groundwater areas, where annual rainfall is less than 400 mm and cotton-wheat, pearl millet-wheat and pearl millet-mustard are the main cropping sequences. Under rice-wheat cropping sequence, groundwater is declining in both fresh and marginal quality groundwater zones. In contrast, water tables are rising in dry zones having poor quality water. In parts of Punjab (Jalandhar, Ludhiana, Moga, Bathinda, Sangrur and Patiala districts) and Haryana (Kurukshetra, Karnal, Kaithal, Jind and Panipat districts), water table has receded by 5–15 m in the last three decades requiring the replacement of centrifugal pumps with submersible pumps leading to more use of energy and higher pumping costs. As any significant decrease in groundwater withdrawal does not seem feasible in the foreseeable future, increase in groundwater recharge through man-made structures including percolation tanks, check dams, recharge tube wells and rainwater harvesting should be given emphasis (Ambast et al. 2006).

9.4 Irrigation Management

Given that decreased freshwater supplies are imminent in the future due to increased municipal-industrial-agricultural competition, available water must be used efficiently (Qadir and Oster 2004). Water use in agriculture, industrial and domestic sectors is 75 %, 20 % and 5 % of the total global consumption (UNEP 2002). The use and reuse of enormous amounts of saline and/or sodic drainage effluents in irrigation will increasingly become necessary (Qadir and Oster 2004). Predominance of saline groundwater aquifers poses a serious limitation to the sustainability of rice-wheat cropping system in India. A set of measures including reduced frequency of irrigation and enhanced irrigation water volumes, replacement of surface irrigation methods with efficient techniques such as sprinkler and drip irrigation, the use of salt-tolerant crops and cultivars, conjunctive use of fresh and saline water, improved fertilizer management and the use of amendments is suggested to overcome many of the problems related to saline irrigation. Either blended or cyclic use of canal water and saline water is desirable in most of the crops. Additional doses of phosphorous and organic manures may be required to alleviate Cl^- toxicity and improved nitrogen use efficiency, respectively (Minhas 1996). Site-specific management practices may enable long-term sustainable use of saline drainage water which is influenced by different factors including the extent of salt leaching, crop establishment method, total rainfall and subsurface drainage. The use of saline drainage water in reclaimed soils will lessen the pressure on freshwater reserves and will also partly reduce the environmental impacts of effluent disposal (Sharma and Tyagi 2004).

Due to significant reduction in water consumption, application of nutrients with water (fertigation) and ease in the use of marginal quality water, drip irrigation is increasingly becoming popular in perennial row crops and fruit trees. The use of poor quality water through drip, however, requires some changes from standard irrigation practices such as selection of appropriately salt-tolerant crops. When using low quality water, drip irrigation has several advantages over other irrigation methods because it does not wet the foliage, and because of its high application frequency, concentrations of salts in the rooting zone remain manageable (Mmolawa and Or 2000). Besides considerable reduction in water-use and energy-use costs coupled with the significant increase in yield, direct water application into root zone means virtually no surface runoff considerably arresting the rate of soil displacement. As irrigation channels and bunds are not required, additional lands can be put under crops. Addition of soluble nutrients and pesticides in irrigation water means efficient use of these resources resulting in reduced cost of cultivation and control of environmental pollution as agrochemical loads into soil and groundwater are minimized (Singh et al. 2007). Long-term use of saline water through surface drip may result in gradual downward movement of salts to the root zone increasing osmotic stress and salt toxicity to the crops. The assumption that such salt accumulation can be overcome by adopting the subsurface drip irrigation (SDI) is based on the premise that salt front is partially driven down into the deeper soil bulk and to the periphery of the root zone under SDI and thus minimizing the risk of damaging the main roots of the plants. Moreover, the improved moisture conditions in the vicinity of the emitter offset the inhibiting effects of the presence of the salts in the saline water (Oron et al. 1999). Subsurface drip irrigation (SDI) refers to the application of water below the soil surface through emitters with discharge rates mostly equal to the surface drip. In general, drip tubes placed 2 cm below the soil surface are considered under SDI (Camp 1998). Subsurface drip systems have been specifically designed for row-planted field and vegetable crops to ensure that surface pipes do not hinder the intercultural operations. They are similar in design but vary with the surface drip in that tubings are buried. In addition to the advantages of surface systems, SDI curtails the water loss due to evaporation and deep percolation and virtually eliminates the surface runoff. It also permits precise application of water and nutrients in the root zone (Roberts et al. 2009).

9.5 Use of Chemicals and Amendments

Excess exchangeable Na^+ in sodic soils is replaced by the application of chemicals and amendments rich in Ca^{2+} followed by leaching with good quality water. A range of factors including the degree of sodicity, depth of reclamation, amendment to be used and crops to be grown determine the extent of reclamation. The efficiency of an amendment vis-à-vis other available options, effects on soil properties and crop growth and the likely expenditure are the major guiding principles in sodic soil reclamation programmes (Abrol et al. 1988). Depending on soil chemical properties, either direct (e.g. gypsum) or indirect (sulphuric acid, elemental sulphur, etc.; Horney et al. 2005) forms of calcium may be applied. In soils low in carbonate, application of gypsum is recommended. Similarly, high carbonate soils may be reclaimed using sulphuric acid and other indirect sources of calcium (Horney et al. 2005). Gypsum is the most widely used amendment in sodic soils. It is, however, becoming evident that gypsum may not be available in desired quantity and quality in the future. While gypsum supplies are becoming scarce with time, both higher costs and poor quality prohibit its use by the farmers. It is likely that gradual reductions in government subsidies and higher market prices will further decrease gypsum availability and use (Qadir and Oster 2004). This state of affairs has enhanced the interest in organic inputs, alternative amendments and nanoscale materials in sodic soil reclamation. It has been shown that the use of easily available and cheap organic amendments increases the productivity of salt-affected lands as organic matter input often accelerates salt leaching and improves aggregate stability, water flux and water-holding capacity (Walker and Bernal 2008). Application of organic inputs such as green manure (Rao and Pathak 1996), farmyard manure (FYM; Ahmed et al. 2010), poultry manure (PM; Tejada et al. 2006), municipal solid waste compost (MSWC; Lakhdar et al. 2009), rice straw (Liang et al. 2005) and olive mill waste compost (OMWC; Walker and Bernal 2008) improves the soil environment and enables better plant growth in salt-affected soils.

Incorporation of *Sesbania cannabina* green manure in highly saline and alkali soils improved the physico-chemical and biological properties as evident from significant reductions in soil pH and exchangeable sodium, increase in soil carbon and nitrogen and enhanced activity of urease enzyme (Rao and Pathak 1996). Saline soils (EC_e ~9 dS m^{-1}) treated with PM at 10 t ha^{-1} exhibited almost tenfold increase in plant stand (~80 %) as compared with sparse vegetation (~8 %) in control soil. Organic matter addition increased the soil structural stability, improved the soil aeration and enhanced the microbial biomass. Amended soils showed high water soluble carbohydrates and better biochemical properties as compared to control plots (Tejada et al. 2006). Application of MSWC enhanced salt tolerance of salinized (4 g l^{-1} NaCl) *Hordeum maritimum* L. plants presumably due to improved chlorophyll and protein stability and higher Rubisco capacity which favoured photosynthesis and thus alleviated salt effect on biomass production (Lakhdar et al. 2009). Soil treatment with PM and OMWC significantly improved the soil chemical environment by increasing the cation exchange capacity (CEC) and soluble and exchangeable-K^+ contents and thus limited entry of Na^+ into the exchange complex. The K^+ and P supplied by these amendments also accounted for better crop nutrition and growth (Walker and Bernal 2008). Measurements of soil microbial biomass (SMB) and soil respiration rate indicated that organic matter incorporation in a saline-sodic soil significantly improved the cumulative soil respiration and SMB in comparison to both gypsum application and control treatments. Poor soil respiration and SMB in degraded soils were due to their low soil organic carbon levels. Following organic material input, an increase in SMB levels and respiration rates suggested that a dormant population of salt-tolerant SMB is present in these soils, which has become adapted to such environmental conditions over time and multiplies rapidly when substrate is available (Wong et al. 2009). These findings are ample to prove that the use of organic amendments can mitigate the salt stress in plants in an economical and environment-friendly way.

Many easily available and low-cost industrial byproducts such as press mud and distillery spent wash significantly improve the soil properties and crop yields in sodic soils. Press-mud application and wheat residue incorporation gave the highest rice and wheat yields in soils irrigated with high RSC (8.5 me l^{-1}) water (Yaduvanshi and Sharma 2007). Similarly, combined use of press-mud (10 Mg ha^{-1}), FYM (10 Mg ha^{-1}) and gypsum (5 Mg ha^{-1}) significantly enhanced rice and wheat yields under continuous sodic irrigation (Yaduvanshi and Swarup 2005). Application of 50 % distillery effluent along with bio-amendments was best in improving the properties of sodic soil and in improved germination and seedling growth of pearl millet

(Kaushik et al. 2005). These results show that alternative amendments could partially replace gypsum in reclamation programmes. A number of polymer-based soil conditioners have also given encouraging results in degraded soils. They improve soil aggregate stability [67] and water permeability (El-Morsy et al. 1991; Wallace et al. 1986). Zeolite application improved water infiltration in a fine-grained calcareous loess soil (Xiubin and Zhanbin 2001). Ca-zeolite application decreased the surface runoff and soil displacement in sodic soils presumably due to reduced clay dispersion, improvement in soil aggregation and the subsequent increase in soil hydraulic conductivity (Liu and Lal 2012). These results indicate that zeolite and other such compounds can prove useful in alleviating stress conditions in degraded soils given that their interactions with other components of soil system and effects on soil microbes and plants are not harmful.

9.6 Plant-Based Solutions for Salinity Mitigation

The use of salt-tolerant crops and cultivars is desirable to sustain the gains from both salt-affected and reclaimed soils. There use can greatly reduce water and chemical amendment use in the reclamation programmes. Saline and sodic soils put under salt-tolerant trees and shrubs show marked improvements in physico-chemical properties after a few years (Sharma and Chaudhari 2012; Sharma and Singh 2015) which is attributed to gradual increase in organic carbon and nutrient contents, better water permeability, higher microbial activity and decrease in soluble salts and exchangeable Na^+ (Mishra et al. 2003; Nosetto et al. 2007). Different tree and shrub species have been identified for raising plantations in salt-affected community lands. The promising species for sodic lands include *Prosopis juliflora*, *Acacia nilotica*, *Casuarina equisetifolia*, *Tamarix articulata* and *Leptochloa fusca* (Singh et al. 1994). In addition to long-term improvements in soil quality, such candidate species are also important from the carbon sequestration perspective and are valuable in alleviating fuel wood and forage shortages in rural areas (Sharma et al. 2014b). Fruit tree-based agri-horti systems (*Aegle marmelos*, *Emblica officinalis* and *Carissa congesta* as main components and cluster bean and barley as subsidiary components) have been identified for areas having marginal quality water (EC_{iw} 6–10 dS m^{-1}) (Dagar et al. 2008). A number of medicinal plants such as *Plantago ovata*, *Aloe barbadensis* and *Andrographis paniculata* perform and yield well under saline irrigation (Tomar and Minhas 2004). Rampant waterlogging and salinity in many irrigation commands have turned thousands of hectares of agricultural lands into barren tracts. Water seepage from canals, excess irrigation and drainage congestion induce water-table rise and salt accumulation in root zone (Chhabra and Thakur 1998). Traditionally, waterlogged lands are reclaimed by SSD. The slow penetration of SSD technology, however, due to prohibitive costs, difficulties in maintenance and environmental issues in drainage effluent disposal (Chhabra and Thakur 1998; Gupta 2002; Ram et al. 2011), has enhanced interest in bio-drainage through salt-tolerant trees (Ram et al. 2011). Bio-drainage involves the planting of salt-tolerant and fast-transpiring trees to pump out the excess water and dissolved salts. This bioenergy-driven technology has proved effective in arresting salinization process in irrigated lands when suitable tree species (e.g. eucalyptus, popular and bamboo) are raised in the beginning (Heuperman et al. 2002). In areas where dryland salinity is emerging as a major form of land degradation, as in southern Australia, planting of perennial trees, shrubs and pastures is suggested to lower the groundwater tables to arrest the process of salinity build-up (Schofield 1992). It is, however, observed that such revegetation plans are hindered by shallow water tables and high salinity in discharge zones. Again, the maximum reduction of water tables from revegetation in discharge areas is only about 2.5 m. These observations indicate usefulness of tree plantations for the localized salinity management in recharge areas (George et al. 1999).

Concerted efforts over the past four decades have resulted in the development of promising salt-tolerant varieties in rice, wheat and mustard. These salt-tolerant varieties provide a viable and cost-effective solution to the resource poor farmers in saline environments by ensuring better and stable yields even with reduced doses or no use of amendments. These varieties also exhibit tolerance to climate variability-induced adverse soil conditions such as waterlogging. There is a growing realization, however, that exclusive focus on breeding for salt tolerance would no longer work and that the development of multiple stress-tolerant crop genotypes must be prioritized by integrating molecular and genomics tools with conventional breeding approaches (Sharma and Singh 2015). In India, the development of salt-tolerant rice varieties started in the 1940s. Initially, varieties such as Pokkali and Jhona 359 were developed through selection from the locally adapted landraces under coastal saline- and inland saline-sodic soil conditions, respectively. Systematic breeding efforts from the 1960s onwards, however, resulted in the development of many promising types for commercial cultivation (Singh et al. 2010). In spite of the availability of a number of improved selections, only a few have become popular among the farmers. The major reasons behind limited adoption by the farmers are low level of salt tolerance relative to the locally adapted landraces and poor grain quality (Singh et al. 2010). The recent trends in the development of salt-tolerant rice cultivars include greater emphasis on quantitative trait loci (QTL) mapping and marker-assisted breeding for introgression of markers tightly linked to the submergence tolerance gene (*SUB1*) and QTL for salinity tolerance at the seedling stage (qSALTOL) in the background of high-yielding cultivars (Singh et al. 2010).

9.7 Saline Aquaculture

Degraded land and water resources in salinity-affected regions can be put to profitable use by shrimp and fish farming (Purushothaman et al. 2014). Over the years, aquaculture using saline groundwater has emerged as a viable land-use practice in many saline tracts of Australia, Israel and the USA (Burnell and Allan 2009). Consistent with the national goals, as mentioned in the 11th Five-Year Plan of Indian

Council of Agricultural Research, efforts have been made to demonstrate the practical feasibility of commercial fish culture in saline lands. Despite very high salinity of pond water (25 dS m^{-1}), limited water availability and high evaporative losses, better fish growth was observed (CSSRI 2013). Seaweed cultivation has also emerged as an attractive option to harness the productivity of poorly drained saline lands. Seaweeds are large, multicellular marine algae and constitute an important renewable resource in the marine environment (Subba Rao and Mantri 2006). They are eaten raw, cooked or processed and have applications in many cosmetic and pharmaceutical products as active ingredients (e.g. seaweed polysaccharides such as agars, carrageenans and alginates). Rising global demand for seafood and declining fish catches have also proved conducive to the growth of this sector (Neoria et al. 2004). Notwithstanding a long coastline (~8000 kms) and rich seaweed diversity, commercial seaweed cultivation is still in a nascent stage in India. Although large tracts of suitable areas are available, seaweed industry suffers from the absence of standardized practices, lack of infrastructure and the absence of policy support. In addition to economic use of saline lands, seaweed cultivation presents several opportunities such as carbon sequestration, provision of breeding grounds for fish and shellfish, pollution abatement and diversified uses as animal feed and fertilizers (NAAS 2003).

9.8 Microbial Approaches for Salinity Mitigation

Of late, the need to exploit the potential of salt-tolerant microorganisms to alleviate salt stress in plants has gained attention. Collectively referred to as plant growth-promoting rhizobacteria (PGPR), these soil microbes upregulate the levels of growth-promoting phytohormones, volatile organic compounds and extracellular enzymes and improve the availability of nutrients for enhanced tolerance to abiotic stresses (Ruzzi and Aroca 2015). As such soil microorganisms exhibit considerable salt tolerance and have potential to promote plant growth in saline and sodic soils (Arora et al. 2014), studies have been carried out to isolate and utilize effective strains in salinity management in different field and horticultural crops. Endophytic bacteria induced sodicity tolerance in polyembryonic mango rootstocks (GPL-1 and ML-2) which was presumably due to higher activity of extracellular enzymes such as amylase, protease, cellulase and lipase (Kannan et al. 2015). The physiological bases of salinity mitigation by these microorganisms include higher uptake of K^+ ions, improvement in water absorption and leaf water relations, stability of chlorophyll pigments and increase in photosynthesis, elevated levels of antioxidant enzymes and expression of genes involved in salt tolerance (Ruzzi and Aroca 2015). Although effective in alleviating salt stress in crops, the use of microbial inoculants is limited due to higher costs and lack of technical know-how. To circumvent these constraints, a low-cost microbial bioformulation 'CSR-BIO', based on a consortium of *Bacillus pumilus*, *Bacillus thuringiensis* and *Trichoderma harzianum* on dynamic media, has been developed. It acts as a soil conditioner and nutrient mobilizer and significantly increases the productivity of crops like rice, banana, vegetables and gladiolus in sodic soils (Damodaran et al. 2013).

Arbuscular mycorrhizal (AM) fungi mitigate the detrimental effects of salinity by regulating key physiological functions including the accumulation of compatible solutes to avoid cell dehydration, regulation of ion and water uptake by roots, reduction of oxidative stress by enhancing the antioxidant capacity and stabilizing photosynthesis for sustained growth (Ruiz-Lozano et al. 2012). Under salt stress (0.1–0.5 % NaCl), AM-inoculated *Jatropha* plants had greater dry weight of shoots and roots, better leaf water status, low lipid peroxidation, higher osmotic adjustment and higher leaf chlorophyll concentrations than non-AM-inoculated plants (Kumar et al. 2010). Two AM strains *Glomus fasciculatum* and *G. macrocarpum*, alone and in combination, improved growth, development and mineral nutrition in salt-stressed *Acacia auriculiformis* plants (Giri et al. 2003). Arbuscular mycorrhizal fungi *Glomus mosseae* alleviated salt-induced reduction of root colonization, growth, leaf area, chlorophyll content, fruit fresh weight and fruit yield in tomato cultivar Zhongzha 105 under NaCl salinity (Latef and Chaoxing 2011). Red tangerine (*Citrus tangerine* Hort. ex Tanaka) seedlings inoculated with AM fungi (*Glomus mosseae* and *Paraglomus occultum*) had better shoot and root growth and produced significantly higher biomass under 100 mM NaCl salinity as compared to non-mycorrhizal controls. Inoculation with AM fungi significantly increased root length and root surface area, improved photosynthesis and reduced leaf Na^+ concentrations resulting in favourable ionic balance in terms of high K^+/Na^+ ratio (Wu et al. 2010).

10 Emerging Constraints in Salinity Research

Evidence is mounting that climate change effects would be more severe in salt-affected environments. Changes in the current temperature and rainfall patterns would cause heavy production losses in arid and semiarid zones (Enfors and Gordon 2007). Sea level rise and the consequent increase in salt intrusion coupled with increased frequency of cyclonic storms would undermine the productivity of coastal agroecosystems (Yeo 1998). As most of the crops are salt sensitive, increase in temperatures would result in more evapotranspiration losses resulting in increased salt accumulation in foliage (Yeo 1998). Coastal aquifers across the world are experiencing enhanced ingress of sea water caused by both natural and anthropogenic processes. The problem seems to have reached critical levels in shallow aquifers located in the vicinity of coastline. Although precise quantitative estimates of the patterns of movement and mixing between freshwater and saline sea water are mostly unavailable, availability of such information is a prerequisite for designing the appropriate prevention and management practices to cope up with this challenge (Ranjan et al. 2006).

In saline and sodic soils, existence of diverse stresses such as excess salts, anaerobic conditions, drought and boron toxicity adversely affects the crop growth and yield. Although simultaneous occurrence of these abiotic stresses proves lethal to plant survival, least is known about the physiological and molecular bases of plant acclimation to two or more stresses. The huge damage caused to agricultural crops by two or more different stresses highlights the need to identify and develop multiple stress-tolerant genotypes (Mittler 2006). To put this into perspective, an in-depth understanding of regulatory framework and functions of stress-induced genes is very important (Bartels 2001). It is expected that emerging technologies such as marker-assisted selection, gene tagging and cloning, functional genomics and proteomics could greatly expedite the conventional approaches for developing multiple stress-tolerant crop cultivars.

The importance of water as a key driver of agricultural development is reflected by the fact that only 19 % of irrigated agricultural land supplies 40 % of the world's food (Hanjra and Qureshi 2010). As severe water shortages are impacting agricultural production in many parts of the world, water-starved arid and semiarid lands having salt-affected soils could be worst affected (Williams 1999). Good quality water availability in desired quantities is of utmost importance for higher agricultural productivity. Besides continuous decrease in the availability of freshwater resources, many parts of India suffering from water scarcity are also usually underlain by poor quality aquifers (Singh 2009). Research priorities have been outlined to standardize the protocols for the use of polluted waters in reclamation, and significant achievements have been made with respect to groundwater recharge, storage and subsequent use of rainwater through land modification and other technological interventions such as *dorouv* technology to skim fresh water floating on the saline water (Shrama et al. 2014a).

The disposal of saline drainage water containing toxic salts and pollutants (Heuperman et al. 2002) into rivers, lakes and seas is neither environmentally acceptable nor economically viable in inland regions. Again, localized disposal may adversely affect the soil and environmental health (Tanji and Kielen 2002; Tripathi et al. 2008). The use of evaporation ponds to dispose such drainage effluents suffers from higher establishment costs and specific design requirements (Tripathi et al. 2008). It thus becomes imperative to utilize the drainage water at the place of origin. The prospects of using drainage water in irrigation are maximized when a source of fresh water is also available so as to use saline water in cyclic and/or blending modes with good quality water (Shennan et al. 1995). Selection of appropriate salt-tolerant crops and varieties would be a key to the success of conjunctive water use (Grattan et al. 2004). Pre-sowing irrigation with fresh water and subsequent use of saline and fresh water in alternate/blended modes have given good results in wheat (Sharma and Rao 1998), and further refinements are being made to widen the scope and practical utility of this technique in other crops.

Besides widespread secondary salinity in irrigated lands, growing instances of resodification (Gharaibeh et al. 2014; Tripathi and Singh 2010) and resalinization (Amin 2004; Valipour 2014) of the ameliorated soils have caught attention. Reclaimed soils support agricultural production for a few years and gradually attain their original state. The adverse conditions which favour reappearance of sodic and saline patches include drainage congestion and shallow water tables (Buckland et al. 1986), canal seepage and subsequent waterlogging (Shakya and Singh 2010), repeated droughts (Fekete et al. 2002) and practice of crop fallow (Tripathi and Singh 2010). The agronomic interventions such as efficient irrigation and drainage techniques, balanced fertilizer use with emphasis on organic inputs, cultivation of low water requiring crops and resource conservation technologies should be adopted to ensure lasting returns from the reclaimed soils (Sharma et al. 2014a).

11 Conclusion and Future Thrust

The food and nutritional security of the burgeoning world population faces a number of formidable challenges such as land degradation, freshwater scarcity and climate change. Available evidences show that these problems are likely to aggravate in the future. It is thus imperative to augment the productivity of existing agricultural lands as well as to bring the abandoned lands under crop production in a socially acceptable and economically viable manner. It is increasingly being realized that current food production and distribution systems have not been able to ensure the food and nutritional requirements of a large chunk of global population. The situation is particularly grim in many underdeveloped and developing countries where problems of salinity-induced land and water degradation have also risen substantially in the last few decades. Although significant achievements have been made to harness the productivity of saline lands, emerging constraints have necessitated a relook at research strategies to fine-tune them to the current and emerging challenges.

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Diagnostic Properties and Constraints of Salt-Affected Soils

Sanjay Arora

1 Introduction

Since time immemorial, the man has been relying on the soil for his sustenance for food, clothes, shelter and energy requirements. The pressure on this vital resource has increased to such an extent that the relationship between the living beings and the soil has become critical. A systematic and scientific appraisal of natural resources, especially soils and their database, is an important parameter, which may help to augment the food production. Soil resource inventory, therefore, is basic for rationalising land use according to its capability. Since no two soils are alike and have their own potential and/or problems and behave differently to management inputs, their use as per their capability is imperative for sustainable agricultural production (Yadav 2008). For sustained utilisation of soil resource, it is imperative to know the nature, characteristics and extent of different soils, their qualities, productive capacity and suitability for alternative land uses. Soil is defined as a naturally occurring body that has been evolved owing to the combined influenced of climate and organisms, acting on parent materials, as conditioned by relief over a period of time.

According to the Glossary of Soil Science Terms (Soil Science Society of America, 1970),

> "Soil is (1) the unconsolidated mineral materials on the immediate surface of the earth that serves as a natural medium for the growth of land plants, (2) the unconsolidated mineral matter on the earth surface that has been subjected to and influenced by genetic and environmental factors of parent materials, climate (including moisture and temperature effects), macro and microorganism and topography, all acting over a period of time and producing a product that is soil, that differs from the material from which it is derived in many physical, chemical, biological and morphological properties and characteristics".

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2 Estimates of Salt-Affected Soils

According to the FAO Land and Plant Nutrition Management Service, over 6 % of the world's land is affected by either salinity or sodicity. The term *salt affected* refers to soils that are saline or sodic, and these cover over 400 million hectares, which is over 6 % of the world land area (Table 1. Much of the world's land is not cultivated, but a significant proportion of cultivated land is salt affected. Of the current 230 million ha of irrigated land, 45 million ha is salt affected (19.5 %), and of the 1500 million ha under dry land agriculture, 32 million is salt affected to varying degrees (2.1 %). In India, about 6.73 Mha of land is affected by salinity and sodicity problems.

2.1 Soil Resources of India

India's share in land resources of the world is only 2 %, on which 18 % of the world's population and over 15 % of the world's livestock survive. However, with its diverse agro-climate, topography and soil types, India is capable of producing a wide range of crops and vegetation. The land surface of the country is spread over an area of 329 Mha and is represented by different types of soils which are given in the Table 2. The Indian soils are broadly classified under eight soil taxonomic orders (Table 3).

Table 1 Regional distribution of salt-affected soils, in million hectares (Mha)

Regions	Total area (Mha)	Saline soils (Mha)	(%)	Sodic soils (Mha)	(%)
Asia, the Pacific and Australia	3107	195	6.3	249	8.0
Europe	2011	7	0.3	73	3.6
Latin America	2039	61	3.0	51	2.5
Near East	1802	92	5.1	14	0.8
North America	1924	5	0.2	15	0.8
Total	12,781	397	3.1	434	3.4

Source: FAO Land and Plant Nutrition Management Service

Table 2 Major soil groups in India

Soils	Area (Mha)
Red and laterite soils	117.2
Black soils	73.5
Alluvial soils	58.4
Desert soils	30.0
Other soils {saline–alkali soils, forest and hill soils, peaty and marshy soils}	49.6

Table 3 Distribution of soils of India

Soil order	Area (Mha)	Percent
Entisols	80.1	24.37
Inceptisols	95.8	29.13
Vertisols	26.3	8.02
Aridisols	14.6	4.47
Mollisols	8.0	2.43
Ultisols	0.8	0.24
Alfisols	79.7	4.25
Oxisols	0.3	0.08
Non-classified	23.1	7.01
Total	328.7	100

The National Bureau of Soil Survey and Land Use Planning, Nagpur, has developed a detailed soil map of the country at soil suborder association level (totalling about 103 soil suborders). The soils were further classified following Soil Taxonomy up to family level.

3 Threats to Soil Resources

The massive post-independence development of irrigation has brought sufficient water for crops in millions of farms in India. Irrigation development, though a major factor in India's ability to enhance food production in irrigated areas and attain self-sufficiency in cereal grain production, in many canal commands, a rise in water table has been noticed consequent leading to the degradation of soils through waterlogging and secondary salinisation.

3.1 Soil Degradation

The primary cause of degradation is the demographic pressure on land, resulting in loss of vegetal cover through deforestation. The land degradation occurs mainly due to uncontrolled deforestation followed by agricultural/farm activities. Hence, planning for productive land use is necessary to meet the growing challenges of food security since the land resource is not expandable physically.

It is estimated that in India, about 174.4 Mha of land is potentially exposed to various degradation forces like water (153.2 Mha) and wind erosion (15.0 Mha). About 40.0 Mha is subjected to floods and 22.0 Mha is not reclaimable for agricultural use. Loss of vegetal cover results in huge run-off, lowered recharge of groundwater and subsequently development salinity**.** Salt-affected soils occur at a tune of

6.73 Mha in our country. Salinisation, or soil degradation caused by increase of salt in the soil, is caused by incorrect irrigation management or intrusion of sea water into coastal soils arising from overabstraction of groundwater (Rao et al. 2014). It is severe on irrigated lands of the dry zone. It reduces crop yield and in severe cases causes complete abandonment of agriculture.

3.1.1 Salt-Affected Soils

In India salt-affected soils are mainly confined to the arid and semiarid and sub-humid (dry) regions and also in the coastal areas. The salt deposits are of sodium carbonate, sulphate and chloride with calcium and magnesium.

- These soils vary in nature from saline to nonsaline sodic.
- In coastal regions, saline soils are most predominant. They have high soluble salts (EC >4 dS/m) of chloride and sulphate of sodium, calcium and magnesium, low ESP and have pH value less than 8.2.

3.1.2 Extent of Salt-Affected Soils in India

The National Remote Sensing Agency (NRSA), Hyderabad, in association with other national and state level organisations like the Central Soil Salinity Research Institute, Karnal; National Bureau of Soil Survey and Land Use Planning, Nagpur; All India Soil Survey and Land Use, Delhi; and state government agencies conducted survey and used remote sensing data to prepare the maps of salt-affected soils of India in 1996. The Landsat satellite images were used in mapping salt-affected soils at 1:250,000 scale. Satellite images were interpreted for broad categorisation of different types of salt-affected soils; sample areas for field verification were identified and surveyed for soil sampling and characterisation. The salt-affected soils were classified according to norms for pH, electrical conductivity (EC) and exchangeable sodium percentage (ESP). The statewise extent of salt-affected soils in India is given in Table 4. It shows that maximum area of salt-affected soils occur in Gujarat followed by Uttar Pradesh and Maharashtra which account for about 62.4 %. Due to the limitation of small scale, some very small and isolated patches of salt-affected soils occurring in the states of Delhi, Jammu and Kashmir and Himachal Pradesh could not be detected. The salt-affected soils account for 6.727 Mha equivalent to 2.1 % of the geographical area of the country.

Out of the total 6.727 million ha of salt-affected soils, 2.956 million ha are saline and the rest 3.771 million ha are sodic. Out of the total 2.347 million ha salt-affected soils in the Indo-Gangetic Plain, 0.56 million ha are saline and 1.787 million ha are sodic.

Table 4 Extent of salt-affected soils India (ha)

State	Saline	Sodic	Total
Andhra Pradesh	77,598	196,609	274,207
Andaman and Nicobar Islands	77,000	0	77,000
Bihar	47,301	105,852	153,153
Gujarat	1,680,570	541,430	2,222,000
Haryana	49,157	183,399	232,556
Karnataka	1893	148,136	150,029
Kerala	20,000	0	20,000
Madhya Pradesh	0	139,720	139,720
Maharashtra	184,089	422,670	606,759
Orissa	147,138	0	147,138
Punjab	0	151,717	151,717
Rajasthan	195,571	179,371	374.942
Tamil Nadu	13,231	354,784	368,015
Uttar Pradesh	21,989	1,346,971	1,368,960
West Bengal	441,272	0	441,272
Total	2,956,809	3,770,659	6,727,468

Source: NRSA & Associates (1996)

Table 5 Properties of saline, saline–alkali and nonsaline–alkali soils

Properties	Saline soils	Saline–alkali soils	Nonsaline–alkali soils
Electrical conductivity (dS m^{-1})	>4.0	>4.0	<4.0
pH	<8.5	>8.5	>8.5
Exchangeable sodium per cent	<15	>15	>15

3.2 Characteristics of Salt-Affected Soils

The term ‘soil’ is considered to be a three-dimensional piece of landscape having shape, area and depth. Saline and alkali soils are defined and diagnosed on the basis of EC and SAR determination made on soil samples, and the information thus generated contributes substantially to the scientific agriculture based on USDA classification given in Table 5.

3.2.1 Natural or Primary Salinity

Salinity primarily results from the accumulation of salts over long period of time, in the soil or groundwater, which is generally caused by two natural processes:

- Weathering of parent materials breaks down rocks and releases soluble salts of various types, mainly chlorides of sodium, calcium and magnesium and, to a lesser extent, sulphates and carbonates. With sodium chloride as the predominant soluble salt.

- The deposition of oceanic salt carried in wind and rain forms the second cause.
- Rainwater contains from 6 to 50 mg kg^{-1} of salt, the concentration of salts decreasing with distance from the coast to the inland areas.
- The amount of salt stored in the soil varies with the soil type, being low for sandy soils and high for soils containing a high percentage of clay minerals. It also varies inversely with average annual rainfall.

3.2.2 Secondary or Human-Induced Salinity

Salinity occurs through natural or human-induced processes that result in accumulation of dissolved salts in the soil water to an extent that inhibits plant growth. Secondary salinisation results from human activities (anthropogenic) that change the hydrologic balance of the soil between water applied (irrigation or rainfall) and water used by crops (transpiration). The important causes for secondary salinisation are the following:

(a) Land clearing and the replacement of perennial vegetation with annual crops
(b) Use of salt-rich irrigation water
(c) Lands having insufficient drainage

3.2.3 Sources and Causes of Accumulation of Salts

The main causes of salt accumulation include:

- Capillary rise from subsoil salt beds or from shallow brackish groundwater
- Indiscriminate use of irrigation waters of different qualities
- Weathering of rocks and the salts brought down from the upstream to the plains by rivers and subsequent deposition along with alluvial materials
- Ingress of sea water along the coast
- Salt-laden sand blown by sea winds

Lack of natural leaching due to topographical situation, especially in arid and semiarid conditions.

Saline Soils These soils will have electrical conductivity (EC) of the saturation extract more than 4 dS m^{-1} and the exchangeable sodium percentage (ESP) less than 15 and the pH is less than 8.5. With adequate drainage, the excessive salts present in these soils may be removed by leaching thus bringing them to normalcy. Saline soils are often recognised by the presence of white crusts of salts on the surface. The important soluble salts in these soils are cations sodium, calcium and magnesium with low amounts of potassium and anions, chloride, sulphate and sometimes nitrate. Owing to the presence of excess salts and the absence of significant amounts of exchangeable sodium, saline soils generally are flocculated, and as a consequence, the permeability is equal to or higher than that of similar nonsaline soils.

Table 6 Indian system of classification

Soil characteristics	Saline soils	Alkali soils
pH	<8.2	>8.2
ESP	<15	>15
ECe	>4 dS m^{-1}	Variable, mostly <4 dS m^{-1}
Nature of soluble salts	Neutral, mostly Cl^-, SO_4^{2-}, HCO_3^- may be present but CO_3^{2-} is absent	Capable for alkaline hydrolysis, preponderance of HCO_3^- and CO_3^{2-} of Na^+

Saline–Alkali Soils These soils will have electrical conductivity of the saturation extract more than 4 dS m^{-1} and the exchangeable sodium percentage greater than 15 and the pH is seldom higher than 8.5. These soils form as a result of combined process of salinisation and alkalisation. As long as excess soluble salts are present, these soils exhibit the properties of saline soils. On leaching of excess soluble salts downwards, the properties of these soils will become like that of nonsaline alkali soils. On leaching of excess soluble salts, the soil may become strongly alkaline (pH reading above 8.5), the particles disperse, and the soil becomes unfavourable for the entry and movement of water and for tillage.

Nonsaline Alkali Soils These soils will have their exchangeable sodium percentage greater than 15, the electrical conductivity less than 4 dS m^{-1} and the pH range between 8.5 and 10. The exchangeable sodium content influences significantly the physical and chemical properties of these soils. As the ESP tends to increase, the soil tends to become more dispersed.

In addition to the parameters proposed by the USDA, Indian scientists considered the nature of soluble salts. Further, the pH value of 8.5 is too high, as isoelectric pH for precipitation of $CaCO_3$ at which sodification starts is 8.2, and mostly the pH is associated with the ESP of 15 or more. The classification of salt affected soils according to the Indian system is presented in Table 6.

4 Constraints

- Excess sodium on the soil exchange complex and/or soluble salts in the soil reduces the productivity of these soils.
- Soil physical condition, particularly soil structure, poses problem of water and nutrient availability.
- These soils show micronutrient deficiency.

4.1 Saline Vertisols

Vertisols and associated soils cover nearly 257 million ha of the earth's surface of which about 72 million ha occur in India. This shows that nearly 22 % of total geographical area of the country is occupied by vertisols. In the central part of India known as the Deccan Plateau, the soils are derived from weathered basalts mixed to some extent with detritus from other rocks. In other areas, particularly in the south, the soils are also derived from basic metamorphic rocks and calcareous clays. Similarly, in the western region, these are derived from marine alluvium that account for nearly 19.6 million ha. Of this about 1.12 million ha are affected by salinity and waterlogging problems. These soils are generally deep to very deep and heavy textured with clay content varying from 40 to 70 %. Further, these are also low in organic carbon content, high in cation exchange capacity, slight to moderate in soil reaction and are generally calcareous in nature. Vertisols, when kept fallow during *kharif* season, are exposed to soil erosion hazards. Their inherent physico-chemical characteristics such as poor hydraulic conductivity, low infiltration rates, narrow workable moisture range and deep and wide cracks pose serious problems even at low salinity level. However, the vertisols of Bara tract in Gujarat are generally very deep (150–200 cm), fine textured with clay content ranging from 45 to 68 % with montmorillonite dominant clay minerals (Rao et al. 2014). The soils exhibit high shrink and swell potential and develop wide cracks of 4–6 cm extending up to 100 cm depth. The soils are calcareous in nature having calcium carbonate ranging from 2 to 12 % in the form of nodules, kankar and powdery form.

4.2 Waterlogged Soils

An area is said to be waterlogged when the water table rises to an extent that soil pores in the root zone of a crop become saturated, resulting in restriction of the normal circulation of the air, decline in the level of oxygen and increase in the level of carbon dioxide. The water table, which is considered harmful, would depend upon the type of crop, type of the soil and the quality of underground water. It may vary over a wide range from zero for rice, 1.5 m for other arable crops and more than 2 m for horticultural and forest plantations. From practical point of view, a working group constituted by the Ministry of Water Resources has suggested the following norms:

Depth to water table (m)	Nomenclature
<2	Waterlogged
2–3	Potentially waterlogged
>3	Safe

Table 7 Extent and distribution of waterlogged and salt-affected soils in India (000' ha)

State	Waterlogged area			Salt-affected area			
	Canal commands	Unclassified	Total	Canal commands	Outside canal	Coastal	Total
Andhra Pradesh	266.4	72.6	339.0	139.4	390.6	283.3	813.3
Bihar	362.6	NA	362.6	224.0	176.0	Nil	400.0
Gujarat	172.6	311.4	484.0	540.0	372.1	302.3	1214.4
Haryana	229.8	45.4	275.2	455.0	NA	Nil	455.0
Karnataka	36.0	NA	36.0	51.4	266.6	86.0	404.0
Kerala	11.6	NA	11.6	NA	NA	26.0	26.0
Madhya Pradesh	57.0	NA	57.0	220.0	22.0	Nil	242.0
Maharashtra and Goa	6.0	105.0	111.0	446.0	NA	88.0	534.0
Orissa	196.3	NA	196.3	NA	NA	400.0	400.0
Punjab	198.6	NA	198.6	392.6	126.9	NA	519.5
Rajasthan	179.5	168.8	348.3	138.2	983.8	NA	1122.0
Tamil Nadu	18.0	109.9	127.9	256.5	NA	83.5	340.0
Uttar Pradesh	455.0	1525.6	1980.6	606.0	689.0	Nil	1295.0
West Bengal	NA	NA	NA	Nil	NA	800.0	800.0
Total	2189.4	2338.7	4528.1	3469.1	3027.0	2069.1	8565.2

Note: NA means data not available; Source: Singh (1994)

The development of waterlogging and soil salinisation upon introduction of irrigation in arid and semiarid regions is a global phenomenon. It is estimated that about 10–33 % of irrigated lands in various countries have adversely been affected due to waterlogging and soil salinisation. It seems that since 1979–1980, the area under waterlogging and soil salinisation is increasing at the rate of 3000–4000 ha per annum. It is estimated that around 4.5 million ha area in India is affected by the problem of waterlogging (Table 7).

4.3 *Coastal Soils: Characteristics and Distribution*

Areas quoted under different soil groups do not appear to have been precisely made since the coastal plains are not yet well defined. Of the two coastlines in India, length of the east coast is higher than that of the west. The continental shelf is more stable than the coast. The continental shelf of 0–50 m depth spreads over 191,972 km^2 and that of 0–200 depth over 452,060 km^2 area. The shelf is wide (50–340 m) along the east coast. The exclusion of economic zone is estimated at 2.02 million km^2.

Practically, no systematic study was earlier made to demarcate the coastal soils based on well-defined scientific indices valid for the different sub-ecosystems in this country. Among the past works, some have suggested 3.1 million hectare area (including mangrove forests), while others suggested 23.8 million hectare under coastal salinity in India. The coastal saline soil has been used by various workers almost synonymously with coastal soil *per se* which is not correct since all coastal soils are not saline in nature. None of the above estimates appears to have been made on sound scientific basis. However, the latest compilation made by Velayutham et al. (1998) on the soil resources and their potentials for different agro-ecological subregions (AESR) of India show total 10.78 million hectare area under this ecosystem (including the islands) in India, which was the first scientific approach for delineation of the coastal soils.

4.3.1 Salient Features of Coastal Problem Soils

Coastal soils in a number of situations are constrained by various technological factors limiting the agricultural productivity and, therefore, merit attention. Salinity in the soils and groundwaters has, however, become a major environmental issue, and excessive salinity in the soil or irrigation water has been considered as the main limiting factor for the distribution of plants in natural habitats. The salient factors in the coastal plains are (1) excess accumulation of soluble salts and alkalinity in soil, (2) predominance of acid sulphate soils, (3) periodic inundation of soil surface by the tidal water and (4) eutrophication and hypoxia. All the above factors affect nutrient balance in soil and, in turn, plant growth.

Salinisation is a major form of land degradation in agricultural areas, including the coastal soils. Statistics about the extent of total salt-affected soils in the world vary. However, general estimates are close to 1 billion hectare, which represent about 7 % of the earth's continental extent. Salinity build-up in coastal soils takes place mainly due to salinity ingress of groundwater aquifers, for which the main factors responsible are (1) excessive and heavy withdrawals of groundwater from coastal plain aquifers, (2) seawater ingress, (3) tidal water ingress, (4) relatively less recharge and (5) poor land and water management.

Attempts have been made on modelling of groundwater behaviour with respect to seawater intrusion. Salt water intrusion takes several forms. Horizontal intrusion occurs as the saline water from the coast slowly pushes the fresh inland groundwater landwards and upwards. Its cause can be both natural (due to rising sea levels) and man induced (say, by pumping of fresh water from coastal wells). Pumping from coastal wells can also draw salt water downwards from surface sources, such as tidal creeks, canals and embayment. This type of intrusion occurs within the zone of capture of pumping wells, which is local in nature, where significant drawdown of the water table causes induced surface infiltration. A third of intrusion is called 'upconing'. Upconing also occurs within the zone of capture of a pumping well, with salt water drawn upwards towards the well from the salt water layer or well existing in deeper aquifers.

Salt Accumulation Salt accumulation in soil affects plant growth in the coastal soil in much the same way as in inland soils except for the effects due to specific toxicity of ions under given situations. Three major types of salt-affected soils exist in the coastal plain.

Soil Fertility With regard to soil fertility, the coastal soils are usually rich in available K and micronutrients (except Zn), low to medium in available N and are having variable available P status. Major portion of the applied N fertiliser is lost through volatilisation.

4.3.2 Coastal Saline Soils

Of all the major ecosystems, which factor in agriculture or food production, 'coastal' has a significant role, wherein about 50–70 % of the global population lives within 100 km of the coastline covering only about 4 % of earth's land. Besides, the ecosystem is highly risk prone and vulnerable causing colossal damage to lives and properties, and this is further compounded due to climate change. Agriculture, on the coastal plain, is constrained by a number of technological, social or anthropological and climatic factors limiting the productivity (Rao et al. 2009).

Coastal saline soils occur along the 6100 km long coastline of India. Salinity problems in coastal areas occurred during the process of their formation under marine influences and subsequent periodical inundation with tidal water and in case of low lands having proximity to the sea, due to high water table with high concentration of salts in it. The coastal soils exhibit a great deal of diversity in terms of climate, physiography and physical characteristics as well as in terms of rich stock of flora and fauna (Rao et al. 2013). These soils comprise deltas, lacustrine fringes, lagoons, coastal marshes and narrow coastal plains or terraces along the creeks. About 3.1 million hectares of coastal soils are widely distributed in the coastal belt of West Bengal, Orissa, Andhra Pradesh, Pondicherry, Tamil Nadu, Kerala, Karnataka, Maharashtra, Gujarat, Goa and Andaman and Nicobar Islands. The coastal soils may be either saline or acid sulphate in nature. The saline soils are dominant with $NaCl$ and Na_2SO_4 with abundance of soluble cations in the order of $Na > Mg > Ca > K$ and chloride as the predominant anion. The major problems encountered in these areas are:

- These lands are subjected to the influence of tidal waves and periodical inundation by tidal water.
- Shallow water table enriched with salt contributes to increase in soil salinity during winter and summer months.
- Heavy rainfall resulting in excess water during *kharif* season.
- Poor surface and subsurface drainage conditions.
- Lack of good quality irrigation water and acute salinity during *rabi* season.
- Poor socio-economic conditions of the farming community limiting introduction of high investment technologies.

4.3.3 Inundation and Flooding of Soils

A flood is an overflow or accumulation of an expanse of water that submerges land. In the sense of 'flowing water', the word may also be applied to the inflow of the tide. 'Coastal flood' is caused by severe sea storms, or as a result of another hazard (e.g. tsunami or hurricane). A storm surge, from either a tropical cyclone or an extratropical cyclone, falls within this category. Coastal flooding is a problem wherever development has occurred adjacent to, or on, beach systems. The problems of maintaining these areas are accentuated by naturally rising sea levels due to global climate change. Floods usually occur when storms coincide with high tides. Very often the problem becomes much more severe with increase in salinity in the flood water caused by breaching or overflowing of the sea dykes, etc. Flooding thus causes significant change in soil properties depending on the soil, hydrological properties of the flood water and duration of flood. Among others, the most significant changes in soil properties of relevance to plant growth are silt deposition, accumulation of salts, erosion of top soil, organic C status in soil, depletion of soil oxygen resulting in lack of plant metabolic activities and overall reduced soil atmosphere causing significant change in soil nutrient dynamics.

Proper diagnosis and identification of contraints will help in successful remediation programme of the problem soils.

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Crops and Cropping Sequences for Harnessing Productivity Potential of Sodic Soils

Y.P. Singh

1 Introduction

Sodicity and salinity are the major abiotic stresses in arid and semiarid regions of the country. In India there are about 6.73 million ha of salt-affected soils, out of which 2.8 million are sodic in nature and primarily occurring in the Indo-Gangetic alluvial plains. These soils are different from arable soils with respect to two important properties, viz. the soluble salts and the soil reaction. Soluble salts in soils may influence the crop production through changes in the proportion of exchangeable cations, soil reaction, the physical properties and the osmotic and specific ion toxicity. The replacement of exchangeable Na^+ with Ca^{2+} requires the application of amendments which can either supply soluble calcium ions directly or induce its solubility from the soil constituents. Nutritional imbalance or specific ion toxicity also adversely affects the yields. For reclamation of these soils, a suitable amendment is required to neutralize the soluble salts. Complete reclamation of these soils is a gradual process and increases with time. Selection of suitable crops and cropping system during and after reclamation is very important. During initial years of reclamation, salt-tolerant varieties of selected crops like rice, barley, wheat and mustard should be grown and gradually shifted to the non-salt-tolerant and high-value crops to get higher income. Due to poor physical properties, the management practices during initial years of reclamation for cultivation of crops in sodic soils are quite different than the same crop grown in normal soils.

The studies conducted at the Central Soil Salinity Research Institute, Karnal, and its Regional Research Station, Lucknow, proved that through the selection of suitable crops and cropping systems along with recommended management practices during and after reclamation of sodic soils, their productivity can be enhanced.

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From the study conducted at CSSRI, Regional Research Station, Lucknow, it has been observed that with the application of reduced dose of gypsum (25 % GR), salt-tolerant varieties of rice should be replaced with high-yielding varieties after 4 years and of wheat after 3 years. If the gypsum is applied at 50 % GR, salt-tolerant variety of rice should be replaced with high-yielding varieties after 3 years and wheat after 2 years or diversify the rice–wheat cropping system with highly remunerative medicinal and aromatic crops like sweet basil in kharif and *Matricaria* in rabi to enhance the productivity potential of reclaimed sodic soils and to save the natural resources. In this chapter, an attempt is made to highlight the reclamation methodology of sodic soils and harnessing their productivity through management of crops and cropping systems during and after reclamation.

2 Area and Distribution of Salt-Affected Soils

Salt-affected soils are commonly found in the Indo-Gangetic plains of Uttar Pradesh, Punjab, Haryana, Rajasthan, Bihar and West Bengal. Different workers have reported variable estimates of salt-affected soils in India. According to the latest estimation in India, salt-affected soils occupy about 6.73 million hectare of land, which is 2.1 % of the geographical area of the country (Sharma et al. 2004). Out of 584 districts in the country, 194 have salt-affected soils (Table 1).

Table 1 State-wise extent of salt-affected soils in India (million ha)

State	Saline	Sodic	Total
Andhra Pradesh	0.78	1.97	2.75
Andaman and Nicobar	0.08	0.00	0.08
Bihar	0.47	1.06	1.53
Gujarat	1.68	0.54	2.22
Haryana	0.49	1.83	2.32
Karnataka	0.02	1.48	1.50
Kerala	0.20	0.00	0.20
Madhya Pradesh	0.00	1.40	1.40
Maharashtra	1.84	4.23	6.07
Orissa	1.47	0.00	1.47
Punjab	0.00	0.15	0.15
Rajasthan	0.20	0.18	0.38
Tamil Nadu	0.01	0.35	0.36
Uttar Pradesh	0.22	1.35	1.57
West Bengal	0.44	0.00	0.44
Total	2.96	3.77	6.73

Source: Sharma et al. (2004)

3 Characteristics of Sodic Soils

These soils have higher proportion of sodium in relation to other cations in soil solution and in exchange complex. These soils contain excess of salts capable of sodic hydrolysis such as sodium carbonate, sodium bicarbonate and sodium silicate and sufficient exchangeable sodium to impart poor physical conditions to soil affecting growth of most plants. These soils have saturated paste pH > 8.5, exchangeable sodium percentage (ESP) > 15 and different levels of salinity (EC). The presence of calcium carbonate concretions at about 1 m depths causes physical impedance for root proliferation. The growth of most crop plants is adversely affected because of poor physical conditions, disorder in nutrient availability and suppression of biological activities due to high pH and exchangeable sodium percentage. These soils are deficient in organic carbon, available N, Ca and Zn.

4 Reclamation and Management of Sodic Soils

The reclamation of sodic soil may require technique modified from that used for reclamation of saline soils. In sodic soils, exchangeable sodium destroys the physical structure of the soil and makes it almost impervious to water. The sodium must first be replaced by calcium cation and then leached downwards and out of root zone. Calcium is often used to replace sodium in sodic soil, all calcium compounds and calcium sulphate (gypsum, $CaSO_4 \cdot 2H_2O$) and is considered the best and cheapest for this purpose. Calcium from gypsum replaces sodium, leaving soluble sodium sulphate in water which is then leached out.

4.1 Major Components of Reclamation Technology

The major technological steps involved in reclamation process consisted of the following:

(a) Delineation of affected areas
(b) Provision of assured water supply/development of irrigation system, preferable through installation of bore wells
(c) On-farm development (land levelling, bunding, construction of field irrigation and drainage channels)
(d) Drainage system development
(e) Application of chemical amendments and leaching
(f) The agronomy of sodic land (including crop selection and cropping pattern, soil fertility management, other improved cultural practices, etc.)

Table 2 Combined effect of gypsum and FYM on sodic soil reclamation

Amendment dose		Grain yield (t/ha)		
Gypsum levels (% GR)	FYM (t/ha)	Rice	Wheat	Change in ESP after wheat
0	0	5.2	1.2	64
25	0	5.3	2.3	55
50	0	5.3	2.4	50
0	20	5.3	2.2	58
25	20	5.8	2.8	45
50	20	5.9	2.9	45
CD (P=0.05)		0.4	0.3	

Source: Singh (1998) Initial pH 10.2, ESP 89

The amount of gypsum to be added depends upon the severity of the sodicity, soil texture and selection of crop to be grown. The studies conducted at CSSRI, Karnal, revealed that application of gypsum at 50 % GR in 0–15 cm soil depth is sufficient to grow shallow-rooted crops. However, a hybrid approach (chemical + biological) developed at CSSRI, RRS, Lucknow, revealed that application of gypsum at 25 % GR and mixing in 10 cm surface layer and growing of salt-tolerant varieties of rice proved economical and sustainable for reclamation of sodic soils (Singh et al. 2009). The chemical amendment should be added only once at the initial stage of reclamation and grow crops continuously to add biomass through root residues to boost further reclamation. Various organic amendments like green manure, compost, farm yard manure, pressmud and crop residues such as paddy straw have also been found effective in reclamation of sodic soils, but their effectiveness as sole application is much lower than the chemical amendments. Decomposition of organic matter improves soil permeability and also increases water-soluble aggregates. Swarup and Singh (1989) observed that the use of FYM in conjunction with gypsum enhanced the yield of rice and wheat significantly over application of gypsum alone. The decomposition of organic matter releases CO_2 and other by-products like acids or acid products depending upon the PO_2 in the soil. These decomposed products enhance solubility of native $CaCO_3$ and thus provide Ca for the removal of exchangeable Na. Organic matter along with inorganic amendment quickens the reclamation of sodic soils. Application of FYM combined with gypsum can help reduce the gypsum dose to half of that needed in the absence of manure. There is, thus, a vast scope for exploiting the synergistic effect of locally available organic materials like FYM, municipal solid waste compost and pressmud for minimizing the dose of chemical amendments and reducing the reclamation cost (Table 2).

5 Management of Sodic Soils

Based upon laboratory, pothouses and field experiments, the CSSRI has developed a technology package for reclamation and management of sodic soils, which is given below.

5.1 Pre-reclamation Management

Pre-reclamation activities involve bunding, levelling and cultivation of fields before amendment application. The institute has standardized the bund size to provide for rain and irrigation water storage and also to prevent water losses through surface runoff (Gupta and Tyagi 1980). It has also been investigated that water application and distribution efficiencies are very closely related to uniformity of levelling (Tyagi 1978). Minimum land slope of 0.1 % to drain excess water has been recommended. Flushing of salts by applying heavy irrigation before amendments application was found helpful in decreasing the amendment dose.

5.2 Amendment Use

Sodic soils require application of an amendment before most crops can be successfully grown. Gypsum, pyrite, sulphuric acid, nitric acid, pressmud, aluminium sulphate, ferrous sulphate and FYM are the amendments used for the reclamation of sodic soils. The result of various experiments proved that gypsum followed by pyrite is the most useful because of their easy availability and cost consideration (CSSRI 1979).

6 Methods of Amendment Application

6.1 Gypsum Application Method

A workable procedure has been standardized for gypsum application to achieve higher efficiency. Field studies have shown that mixing gypsum in shallow depths was more beneficial than mixing in deeper depths (Khosla et al. 1973). Mixing limiting quantities of gypsum in deeper depths results in its dilution and, therefore, lesser so improvement. The effect of various gypsum doses on crop yields is given in Table 2.

6.2 Pyrite Application Method

Like gypsum, pyrite can also be used for the reclamation of sodic soils in areas where it is locally available. Studies at CSSRI showed that efficiency of pyrite in reclamation of sodic soils is governed by the soluble S content of the material at the time when it is applied in the field (Sharma and Swarup 1990). From the experiments, it has been observed that pyrite to be effective for reclamation must contain at least 5–6 % soluble S. Better efficiency of pyrite was obtained when it was placed

Table 3 Combined effect of gypsum and farm yard manure on amelioration of sodic soil

Application rate		Grain yield (Mgha^{-1})						Soil pH$_2$		ESP	
		Rice			Wheat			After wheat		After wheat	
Gypsum (%GR)	Manure (Mgha$^{-1)}$	1989	1990	1991	1989	1990	1991	1990	1991	1990	1991
Nil	NIL	3.0	0.45	5.2	0.2	1.0	1.2	10.0	9.7	74	64
25	NIL	5.1	5.2	5.3	1.7	2.2	2.3	9.6	9.4	59	55
50	NIL	5.4	5.5	5.3	2.0	2.3	2.4	9.5	9.3	51	50
Nil	20	4.0	5.2	5.3	1.4	2.0	2.2	9.7	9.5	66	58
Nil	20	4.0	5.2	5.3	1.4	2.0	2.2	9.7	9.5	66	58
25	20	5.8	5.8	5.8	2.1	2.8	2.8	9.4	9.2	46	45
50	20	6.1	6.0	5.9	2.4	2.8	2.9	9.3	9.1	42	45

on the soil surface than when it was mixed in shallow soil depth. Further keeping soil moist for 10–15 days increases the pyrite efficiency by improving its oxidation (Sharma and Swarup 1990).

6.3 Organic Manures Application Method

The organic matter content of sodic soils is often very low organic manure, including farmyard manure; compost and green manures have long been known to facilitate the reclamation of sodic soils. The effect of organic matter application followed by leaching with ponding water has proved beneficial. Decomposition of organic matter results in the evolution of carbon dioxide and organic acids, lowering of soil pH and release of cations by solubilization of $CaCO_3$ and other soil minerals, thereby increasing the electrical conductivity and replacement of exchangeable sodium by cations like calcium and magnesium and thus lowering the ESP (Chhabra and Abrol 1977). Organic matter along with inorganic amendment quickens the reclamation of sodic soils. Application of FYM can help reduce the gypsum requirement to half of that needed in the absence of manure (Table 3).

6.4 Biological Reclamation Method

The biological reclamation approach aims at the reclamation of sodic soils by growing salt-tolerant crops and their varieties. It should not be considered a substitute for chemical reclamation technology, but it is an alternate approach for reclamation of those sodic soils where resource poor farmers cannot afford chemical amendments. In this approach, sodic-tolerant varieties of rice (CSR-10, CSR-13, CSR-23, CSR-27, CSR-36 and CSR-43), wheat (KRL1-4, KRL-19, KRL-210 and KRL-213) and mustard (CS-52, CS-54 and CS-56) are grown for specific period of time either without amendment application or with a small dose of gypsum (Singh et al. 2009).

Table 4 Promising varieties of important crops released and in pipeline for cultivation in sodic soils

Crops	Varieties	Tolerance level
Rice	CSR10	pH 9.8–10.2
	CSR 13, CSR 23, CSR 27 CSR 36, CSR 43, CSR 46	pH 9.4–9.8
	CSR30 (Basmati)	pH 9.4
Wheat	KRL 1-4, KRL 19, KRL 210, KRL 213, KRL 283, WH157, Raj 3077	pH 9.2–9.3
	HD2009, HD2285, PBW343, HD2329,	pH 8.7–9.0
Mustard	CS52, CS54, CS56, CS 58	pH 9.0–9.2
	Pusa bold, Varuna, Kranti	pH 8.8–9.0
Barley	CSB 1, CSB2, CSB 3, Ratna	pH 9.3
Gram	Karnal chana No. 1	pH 8.8–9.0
Sugar beet	Ramonaskaya-06, Polyrava-E	pH 9.5–10
Sugarcane	CO453, CO1341, CO6801, CO62329, CO1111	pH < 9.0

Cultivation of salt-tolerant varieties of rice during kharif and sugar beet in the rabi cropping sequence for 3 years brings down the soil pH from 10.0 to 9.3. In the fourth year and later on, rice in kharif and wheat or raya in rabi can be taken successfully (Table 4).

7 Selection of Crops and Cropping Sequences

Selection of proper crop in the initial stages of reclamation is very crucial because crop differs widely in their tolerance to soil sodicity. Some crops are sensitive, whereas others are either semi-tolerant or tolerant to a given level of sodicity (Table 5). The selected crops should not only be tolerant but should also exert reclaiming effect on the soil. Therefore in the initial years of reclamation, only tolerant crops should be grown and gradual choice may be shifted to relatively less tolerant and sensitive crops. Amongst the agricultural crops, rice in kharif season is most ideal as the first crop because it can tolerate standing water and has very high tolerance to sodicity, extensive shallow root system and ability to accelerate availability of native Ca for replacement of exchangeable Na through root activities, and in rabi season, only shallow-rooted crops like wheat, barley, berseem and mustard could be grown in the initial years (Yadav and Agarwal 1959). In Uttar Pradesh, rice in kharif season followed by berseem, wheat or barley in winter season reported better crops in the initial years of reclamation. When salt-tolerant varieties of rice were grown in crop sequences for 3 years, the reclamation of sodic soils was increased and the pH of surface soils reduced, and it becomes possible to grow highly value crops like oil seed crops (mustard, linseed) and medicinal and aromatic crops (tulsi and *Matricaria*) (Singh et al. 2008). The study conducted at CSSRI, Regional Research Station, Lucknow, determined the time frame for substitution of

Table 5 Relative crop tolerance to sodicity

ESP range		
30–50	20–30	<20
Moderately tolerant	Semi-tolerant	Sensitive
Barley	Linseed	Bengal gram
Mustard	Garlic	Soya bean
Rapeseed	Sugarcane	Maize
Wheat	Cotton	Safflower
Sunflower	Guar	Peas
Sorghum	Groundnut	Lentil
Shaftal	Onion	Pigeon pea
Berseem	Pearl millet	Urdbean
	Tulsi	
	Matricaria	
	Bakla	

Table 6 Effect of gypsum alone and in combination with green manure on rice grain yield

Treatments	Grain yields (t/ha)					
Years	2005			2006		
Cropping system	R-W	D-R-W	Mean	R-W	D-R-W	Mean
Control	3.06	3.41	3.24	3.45	3.66	3.56
25 % GR	3.43	4.23	3.83	4.31	4.62	4.47
50% GR	3.78	4.52	4.15	4.49	4.94	4.72
Mean	3.42	4.05	–	4.08	4.41	–
CD (0.05)	*G* = 0.21			*G* = 0.16		
	CS = 0.22			CS = 0.17		
	G × CS = 0.08			G × CS = 0.12		

R-W rice–wheat, *D-R-W* dhaincha–rice–wheat

salt-tolerant varieties of rice and wheat with non-salt-tolerant high-yielding varieties or high-value crops to get higher return (Singh et al. 2010).

In recent years, the tolerance of several forage grasses under greenhouse and field conditions has been evaluated, and Karnal grass (*Leptochloa fusca (Linn.*)), Rhodes grass (*Chloris gayana Kunth*), Gatton panic (*Panicum maximum*), Bermuda grass (*Cylodon dactylon (Linn.*) Pers) and Para grass (*Brachiaria mutica (Forsk*)) were found relatively more tolerant grass species (Kumar and Abrol 1986).

Selection of a suitable cropping system at initial stage of reclamation hastens the reclamation process of sodic soils through addition of root biomass in the soil profile. Salt-tolerant varieties of rice in kharif followed by salt-tolerant varieties of wheat in rabi and dhaincha (*Sesbania*), green manuring in summer has been found most suitable during the initial stage of reclamation. The Central Soil Salinity Research Institute has identified or developed salt-tolerant varieties of various important crops with their tolerance level of sodicity (Table 6).

Table 7 Cropping sequences recommended at different stages of reclamation

Soil pH_2	Reclamation period (years)	Cropping sequences
Initial stages of reclamation		
9.2–9.8	1–3	Dhaincha-Rice–wheat
		Rice–berseem
		Rice–mustard
		Rice–barley
Post-reclamation period		
9.0–9.2	4–5	Sorghum–wheat or mustard
		Pearl millet–wheat or mustard, cotton–wheat
8.8–8.9	6–8	Groundnut–mustard or wheat
		Sunflower–wheat, maize–linseed
		Tulsi–*Matricaria*, chilli–garlic
		Sorghum–mustard–sugarcane
8.6–8.7	9–10	Sorghum–gram or pea
		Pearl millet–lentil or gram
		Pigeon pea–wheat
		Soya bean–wheat
8.5–8.6	After 10	All cropping sequences including vegetables and flowers

Results of several agronomic trials, having various rice-based cropping sequences, have shown that rice–wheat–dhaincha and rice–berseem cropping sequences were more remunerative in sodic soils. This rotation should continue for at least first 3 years, and the field should not be left fallow to ensure continuity of reclamation process and to avoid reversion of sodic conditions. Growing of rice often promote a more favourable physical condition in sodic soils. Recent studies on cropping sequences with rice and sorghum (fodder-based cropping sequences) revealed that rice-based cropping sequences were better than sorghum-based cropping sequences in terms of yield as well as reclamation of sodic soils. These studies further revealed that rice–berseem cropping sequence was best followed by rice–mustard and rice–wheat (Table 7). The study conducted at CSSRI, Regional Research Station, Lucknow, revealed that after 3 years of rice–wheat cropping system, some high-value crops like tulsi, *Matricaria*, garlic and linseed may be grown successfully (Singh et al. 2008). Some of the oil seed crops like sunflower, mustard, safflower, linseed, groundnut, soya bean and sesame were tested for their performance in sodic soils. It was observed that mustard, rapeseed and sunflower were moderately tolerant, linseed and groundnut semi-tolerant and the rest of the crops were sensitive to sodicity.

Results of several field experiments with various cropping sequences conducted at different places have shown that dhaincha-rice–wheat, rice–berseem, rice–mustard and rice–wheat are more remunerative at the initial stage of reclamation of sodic soils. Studies conducted to determine the time frame for crop diversification revealed that diversification of rice–wheat cropping system depends on the extent of reclamation; however, it can be possible after 3 years of continuous rice–wheat cropping system (Singh et al. 2010).

8 Improved Crop Management Practices

Rice and wheat are the major crops grown during and after reclamation of sodic soils. Poor germination and mortality of young seedlings are general problems in sodic soils. Establishing a good crop stand in sodic soils is a challenging task. Nursery management including seed density, age of seedlings and nutrient management is very important management practices for higher productivity of rice. Resorting to closer spacing and increasing the number of seedlings per hill and nutrient management in main field are equally important in case of transplanted rice crop (Singh et al. 2016).

8.1 Nursery Management

8.1.1 Seed Treatment

To control bacterial leaf blight, bacterial leaf streak and some other seed-borne diseases soak the seed for 8–10 h in 10 l water containing 10 g ceresin wet or 10 g agallol or 5 g tafasan/aretan/emisan 6 and 1 g streptocycline before sowing to ensure healthy, sturdy and uniform seedlings in the nursery bed. The use of disease-free seed helps in reducing primary inoculums of many diseases, e.g. bacterial leaf blight, sheath rot, brown spot and kernel bunt. Treat the seed with bioformulations like CSR-Bio at 300 ml/10 kg seed or Halo-Azo and Halo-PSB (salt-tolerant strains of *Azotobacter* and PSB) soaked in 10 l water for at least 8–10 h will help in plant growth promotion and controlling fungal diseases.

8.1.2 Seed Rate and Nursery Bed Preparation

Due to poor physical conditions of sodic soils, mortality of young seedlings occurs and tillering is reduced than the normal soils. Thus sodic soils, in the initial stage of reclamation needs higher seed rate. Nursery should be raised in normal soils. About 40 g seed/m^2 is recommended. About 800–1000 m^2 area for seedlings is required for transplanting in 1 ha rice. For vigorous growth of seedling and better agronomical management, nursery should be grown on raised bed. In the case of jowar, bajra, wheat, barley, mustard, berseem and other crops, about 25 % higher seed rate over the recommended rate is required to ensure good crop stand.

8.1.3 Time of Nursery Sowing and Age of Seedlings

The young seedlings of rice are very sensitive to sodic condition; hence, older seedlings are recommended for transplanting in sodic soils. Generally transplanting of rice in salt-affected soils is done after onset of monsoon. For timely transplanting, nursery should be sown on the first week of June. Thirty days older seedlings are best suited for sodic soils (Singh et al. 2016). The optimum time for transplanting of high-yielding and medium duration varieties is from the first week of July to fifteenth of July. After that, the yield is decreased. Medium duration varieties should be transplanted from middle of July to end of July. The optimum time for sowing of other crops in sodic soils is the same as adopted in normal soils. In the initial years of reclamation, 3–4 seedlings/hill should be transplanted at 20 cm row to row and 15 cm plant to plant spacing. After 3 years of reclamation, spacing may be increased like a normal soil and number of seedlings/hill may also be reduced to 2–3.

8.1.4 Nutrient Management

Application of 125 kg N + 60 kg P_2O_5 + 40 kg K_2O (25 kg N through 5 t/ha FYM at the time of field preparation) and remaining 100 kg N should be applied in three splits 50 % as basal and remaining 50 % at 10–12 days and 20–22 days after sowing. Full dose of P_2O_5 and K_2O should be applied as basal at the time of sowing. Apply 25 kg /ha zinc sulphate (20 % zinc) at the time of sowing. For transplanting, 1 ha area 1/10 or 1000 m^2 area is required to sow the nursery. For 1000 m^2 area, seedbed needed 2.5 kg N through FYM (500 kg FYM), 10 kg N through urea (21.7 kg urea, if FYM not available 26 kg urea), 6 kg P_2O_5 from single super phosphate (37.5 kg SSP), 4 kg K_2O from muriate of potash (6.6 kg MOP) and 2.5 kg zinc sulphate (Singh et al. 2016).

8.2 Method of Transplanting/Sowing

Plough and harrow the field at least three times (two ploughing and one harrowing or one ploughing and two harrowing) to control the weeds. Before transplanting of rice, puddle the field and level it properly. If available, apply compost uniformly short before soil preparation in the field and incorporate. For better weed and nutrient management and higher yield, rice should be transplanted in rows. In the case of other crops like sorghum, pearl millet cotton, wheat, mustard, etc., flat sowing by drilling is recommended. In the case of forage crops like berseem, saftal, etc., sowing may be done in standing water. Furrow planting may help in obtaining better crop stand and yield.

8.3 Nutrient Management

Proper nutrient management in salt-affected soils is very important because of high salt concentration, poor physical conditions and low fertility status. Time and method of fertilizer application in sodic soils is different than the normal soils because of high N losses through volatilization in sodic soils. Based on field experiments, around 20–25 % higher amount of N-fertilizer than the recommended dose of N for normal soils should be applied. It is recommended that N should be applied in split applications. If available, apply 10 t/ha farm yard manure/compost at the time of land preparation. The optimum dose of nitrogen for rice and wheat in sodic soils has been found to be 150 kg/ha. In the case of short-duration varieties of rice, optimum dose of N is about 120 kg/ha. No response to phosphorus application has been reported in rice–wheat cropping sequence initially for 3–4 years. Nitrogenous fertilizer should be applied in split doses to reduce loss of nitrogen in volatilization and denitrification. From the experiment, it is observed that, in rice and wheat crops, nitrogen should be applied in three splits, half or one third at transplanting/sowing and remaining in two equal splits at 3 and 6 weeks after transplanting. Sodic soils are generally deficient in zinc and most of the crops respond favourably to application. Application of zinc sulphate significantly increased the grain yield of rice and berseem fodder as compare to no zinc application. Application of zinc at the rate of 25 kg $ZnSO_4$/ha on a regular basis to rice–wheat crop sequence was sufficient to produce more yields. For other crops, about 20 % of addition nitrogen should be added over the recommended dose of N because of more N losses through volatilization in sodic soils.

8.4 Irrigation Water Management

Water management for crop production in sodic soils is entirely different from the one that is practised in normal soils because of differences in their physical and chemical properties. The water intake rate of sodic soils is very low as compared with normal soils. In these soils, water accumulates following a rainstorm or a heavy irrigation. This water remains on the soil surface for a longer period until it evaporates. The soil surface of these soils gets dried up very quickly during the drying process particularly in summer months, but there is no change in the water content below 15 cm depth.

Rice is the principal crop to be grown in sodic soils during kharif season. Rice needs submerged moisture regime for optimum grain yield. High-yielding, dwarf rice varieties require shallow water for higher crop yield. The total irrigation requirement of this soil is considerably reduced in comparison to normal soil. Application of 7 cm irrigation water after a day of disappearance of ponded water produced much grain yield as compared to continuous submergence (Singhandhupe and Rajput 1989). The yield of wheat crop was significantly higher when first irrigation at crown root initiation (CRI) stage was given 30 days after sowing then at 21 DAS in sodic soil. Five irrigations scheduled at CRI, tillering, jointing, milking and dough stages resulted in higher yield, which was closely followed by treatment in which irrigation at tillering and dough stages were skipped and flowering stage was added.

9 Crop Management for Saline Soils

9.1 Selection of Crops and Cropping Sequences

The selection of crops and cropping sequences for saline soils is of paramount importance, because crops vary their tolerance to salinity. They are either too sensitive or semi-tolerant to tolerant to a given level of salinity (Mass and Hoffman 1977). A classification of various crops according to their tolerance is given in Table 8. In the early phase of reclamation, the crops that are tolerant and can cope up with salinity should be preferred. Appropriate cultivation practices and growing of suitable crops help in leaching of salts. In saline soils of arid and semiarid region, cotton, sorghum, pearl millet, cluster bean and moth bean should be grown during *kharif* and wheat, barley, mustard and safflower during *rabi* (Table 8).

The cultivation of crops having low evapotranspiration or high tolerance is one way of compensating for water deficiency. The recommended cropping sequences for saline soils are pearl millet–barley, pearl millet–wheat, pearl millet–mustard or sorghum–wheat or barley (Singh and Sharma 1991).

Table 8 Crop groups based on response to salt stress

Sensitive group/resistant group			
Highly sensitive	Medium sensitive	Medium tolerant	Highly tolerant
Lentil	Radish	Pearl millet	Barley
Mash	Cowpea	Desi babool	Rice sugar beet
Chickpea	Broad bean	Spinach	Cotton
Beans	Vetch	Sugarcane	Sunflower
Peas	Cabbage	Raya	Taramira
Carrot	Cauliflower	Rice	Turnip
Onion	Cucumber	Wheat	Karnal grass
Lemon	Gourd	Alfalfa	Date palm
Orange	Tomato	Blue panic grass	Safflower
Grapes	Sweet potato	Para grass	*Tamarix*
Plum	Millet	Sudan grass	*Salvadora*
Pear	Maize	Guava	Mesquite
Apple	Berseem	Pomegranate	

9.2 Cultural Practices

In saline soils, germination is adversely affected. Mortality of young seedlings and poor tillering are the major problems. The higher seed rate and closer spacing are advisable to counter these problems. In case of transplanted crops, the number of seedlings per hill should be increased to compensate any loss in their germination. Method of sowing/planting can also be modified to obtain a favourable salt distribution in relation to seed location or growing roots. Furrow planting may help in obtaining better crop stand and yield because salts tend to deposit on the ridges under furrow method of irrigation. Similarly, in case of sugarcane, trench method of planting gave significantly higher yield than flat sowing (Dargan et al. 1973).

9.3 Soil Fertility Management

The salt-affected soils are often poor in most of the essential plant nutrients owing to lack of vegetation and low organic matter content. Nitrogen deficiency is widespread in saline soils. A large amount of the applied nitrogen is lost in gaseous form because of high soil salinity. Availability of phosphorus in these soils increases up to a moderate level of salinity and thereafter it decreases. Saline soils are medium to high in available potassium, but plants grown under high salinity may show K deficiency due to antagonistic effect of sodium and calcium on potassium absorption. Under such conditions, potassium fertilizer should be applied. Nitrogenous fertilizer should be applied in split dose to reduce nitrogen losses through volatilization and densification. The required quantity of phosphorus and potash along with first dose of nitrogen should be applied at or before sowing. The remaining quantity of nitrogen should be applied in two equal splits at first and second irrigation.

9.4 Crop Management

Tolerance to salinity varies a great deal, almost tenfold, amongst the crop plants and to a lesser extent amongst their genotypes. These inter- and interagenic variations in salt tolerance of plants can be exploited for selecting crops or varieties that produce satisfactorily under a given root-zone salinity. The information on crop tolerance to salinity and saline waters can be obtained from Mass (1986) and to the use of saline waters in different agro-climatic zones of India from a compilation by Minhas and Gupta (1992).

Farmer should select salt-tolerant crops. The experiments conducted at Agra centre and found that the following crops may be grown with saline and sodic waters (Table 9).

Table 9 Salt-tolerant crops with relative yield of 90, 75 and 50 % at different ECiw levels

Crops	Previous crop	ECiw (dS m^{-1}) for relative yields		
		90 %	75 %	50 %
Cereals				
Wheat	Pearl millet	6.6	10.4	16.8
Wheat (late)	Toria	4.3	6.6	11.0
Barley	Fallow	7.2	11.3	18.0
Rice	Berseem	2.3	4.6	8.6
Pearl millet	Wheat	5.4	9.0	15.0
Sorghum (seed)	Mustard	7.0	11.2	18.1
Sorghum (fodder)	Berseem	5.2	10.2	18.4
Oilseeds				
Mustard	Sorghum	6.6	8.8	12.3
Toria	Wheat	4.7	5.1	5.9
Pulses/legumes				
Pigeon pea	Onion	1.3	2.3	3.9
Berseem	Rice/sorghum	2.5	3.2	4.4
Soybean	Wheat	2.5	4.7	8.4
Vegetables				
Onion	Pigeon pea	1.8	2.3	3.3
Potato	Okra	2.1	4.3	7.8
Okra	Potato	2.7	5.6	10.5

Source: Bhudayal et al. (2011)

9.5 Crop Varieties

In addition to intergenic variations of different crops to tolerant salinity or sodicity, there is also a wide variation in the inherent salt tolerance of the crop varieties. Though most of research endeavours till now have been aimed at identifying the genotypes and breeding new varieties of crops for normal soil conditions, limited efforts have also been made in this respect for saline environments. Usually there is negative correlation between tolerance of varieties and their potential yields. Hence, there are not many varieties that are both tolerant to salinity and produce economic yield, which is a major consideration for most farmers.

Most of the crop plants are sensitive during the stage of emergence and early seedling growth. This may cause either poor plants stand or delayed germination. The higher concentration of the salts at the soil surface caused by evaporation casts bad effect again on the crop. The relative sensitivity of some crops for irrigation with poor quality water is given in Table 10.

In sodic water/soils, only tolerant and semi-tolerant crops having low water requirement crops, viz. barley, wheat, mustard, pearl millet and sorghum, should be grown. High water requirement crops (rice, sugarcane and berseem) should be avoided.

Table 10 Relative sensitivity at various crop growth stages of different crops

Crops	Relative sensitivity
Mustard	Pre-sowing > flower initiation > secondary branching
Wheat	Pre-sowing > flowering > milking > crop root initiation > jointing
Barley	Crown root initiation > pre-sowing > flowering/booting > jointing
Safflower	Pre-sowing > rosette > flower initiation > main head opening

If good quality canal water is not available, *kharif* season crop should be taken only through rain water to provide salt-free atmosphere for *rabi* crop which is precious and main to the farmer. Sodic water should not be used for growing summer crop.

If saline water is used for pre-sowing irrigation, 20 % extra seed rate and a quick post-sowing irrigation will ensure better germination.

10 Management of Waterlogged Sodic Soils

Traditional sodic land reclamation technique is not suitable for reclaiming waterlogged sodic soils due to shallow water table conditions. With the application of gypsum, soil pH can be brought down and crops can be grown for a year or two, but thereafter soil becomes again sodic. There was a need to develop alternate sodic land reclamation and management techniques. Land modification was thought as one of the effective methods of waterlogged sodic soil management in seepage prone areas.

10.1 Fish Pond-Based Integrated Farming System Model

Excessive seepage is the prime cause of waterlogging in canal commands. Due to excessive seepage in waterlogged sodic soils, salts underneath the soil keeps on moving along with seepage water; hence, pH reduces as one move to deeper soil profile. If normal pH from deeper soil profile could be brought on the top of the soil surface, the same can be used for crop cultivation without adding any amendments in waterlogged sodic soils. Land modification may prove beneficial in making waterlogged sodic soil fertile without amendments. Excavation of huge quantity of soil may require huge investment; hence, immediate production needs to be restored. Fish pond-based integrated farming system has a potential to produce fish right after the digging of pond. The soils excavated from deeper soil profiles can be spread around or on one side of the pond which will elevate the field levels for crop production. Integrated farming approach will further enhance the productivity of the waterlogged areas. A pond depth of 1.5 m to 2.0 can be thought of over an area of one acre which will create an additional upland agricultural land over an area of 1.5–2.0 acre with an average elevated field bed of 0.75–1.0 m. This type of model may require nearly one hectare of area. An experiment over an area of one hectare of land (pond in one acre and elevated fields in 1.5 acre) gave encouraging results.

10.2 Raised and Sunken Bed-Based Farming System Model

This technology is useful for any size of field. If good soil prevails at a depth of 50–80 cm below ground surface, this type of model can be worked out. Normal or low pH soil from deeper soil profiles (50–80 cm) could be brought on the soil surface to form a system of alternate raised beds (2–5 m wide and 0.50–1.5 m depth) and sunken beds (5–10 m wide and 0.5–1.50 m deep). Once the top soil is inverted over raised bed and good soil is exposed in sunken beds, the area can be brought back to cultivation without addition of any gypsum in the soil. Raised and sunken bed is one of the examples of land modification for successful crop production in waterlogged sodic soil for small to medium land holding. Raised beds could be utilized for growing upland crops and sunken beds for water-loving crops. Raised and sunken bed system combines effect of subsurface drainage and amendment-based reclaimatory effect. Good soil exposed allows crops to grow and application of continuous water slowly reclaims deeper soil profiles. An experiment with 2 m wide raised beds and 7 m wide sunken beds with 0.50 m soil digging for raised and sunken beds system in waterlogged sodic soils in Sharda Sahayak Canal Command, Raebareli, also gave an encouraging result. Fish pond-based integrating farming system model is suitable for large land holding.

Large-scale adoption may require calculation of fish pond area, area of elevated fields and its dimensions, raised bed width and height for keeping the efficacy of the system intact and cost at low level. Too wide raised beds may lose their effectiveness in controlling water table, and too short width will be effective but cost may shoot up. Similarly large elevated field area along fish pond may also lose its effectiveness in keeping salts away from soil surface. A necessity was felt to develop design relationship of raised bed width and its height. Further necessity is felt to develop design criteria for these calculations. Steady state and transient drain spacing formulas have been adopted for raised width and height calculation.

11 Conclusion

Selection of crops and adoption of management practices developed after scientific consideration can only ensure successful crop production in salt-affected soils. Since the salt-affected soils vary considerably in their nature and characteristics, it is imperative that only location-specific management practices should be developed and adopted.

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Bio-amelioration of Salt-Affected Soils Through Halophyte Plant Species

Sanjay Arora and G. Gururaja Rao

1 Introduction

Halophytes are remarkable plants that tolerate salt concentrations that kill 99 % of other species. However, although halophytes have been recognized for hundreds of years, their definition remains equivocal. Definition on its ability is "to complete the life cycle in a salt concentration of at least 200 mm NaCl under conditions similar to those that might be encountered in the natural environment" (Flowers et al. 1986). Adopting a definition based on completion of the life cycle should allow separation of what might be called "natural halophytes" from plants that tolerate salt but do not normally live in saline conditions. Other classifications of halophytes have been suggested that are based on the characteristics of naturally saline habitats or the chemical composition of the shoots or the ability to secrete ions. However, although saline habitats do differ in many regards (e.g., soil water content) and differences do exist among species in the balance of Na^+ and K^+ in shoot tissues, we have not, at this stage, embraced the suggested subdivisions of halophytes, as the underlying mechanisms remain unclear (salt glands expected). The general physiology of halophytes has been reviewed occasionally (Flowers et al. 1986) and since then other reviews have examined their ecophysiology, photosynthesis, response to oxidative stress, and flooding tolerance as well as the physiology of sea grasses. The potential of halophytes as donors of tolerance for cereals (Colmer and Voesenek 2009) and as crops in their own right has also been reviewed (Glenn and O'Leary 1984; Colmer and Voesenek 2009), as have the effects of salinity on plants in general.

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In the following pages, we discuss the basic physiology of salinity tolerance in halophytes—growth, osmotic adjustment, and compatible solutes; limitations of space have precluded a review of transpiration in halophytes and of salt glands.

2 What Are Halophytes?

The prefix "halo-" and root "-phytes" are translated as salt and plant, respectively. Thus halophytes are often described as salt-tolerant, salt-loving, or saltwater plants, whereas practically all of our domesticated crops are considered glycophytes ("glyco" or sweet) having been selected and bred from sweet or freshwater ancestors. Halophytes are generally defined as rooted seed-bearing plants (i.e., grasses, succulents, herbs, shrubs, and trees) that grow in a wide variety of saline habitats from coastal sand dunes, salt marshes, and mudflats to inland deserts, salt flats, and steppes. Halophytes occupy niches from the marine to the arid, from salt deserts to salt marshes, and this range of habitats is reflected in a variety of recognized "physiotypes." Halophytic plants provide options for livestock feeding in both arid and saline landscapes. These plants are variable in both biomass production and nutritive value; they are characterized by slow growth, low digestibility (therefore low metabolizable energy), and high content of anti-nutritional factors. These highly adaptable plants, which can accrue relatively large amounts of salt, are found in every climatic zone where there is vegetation, from the tropics to tundra. Halophytes have been divided into two groups, obligative halophytes, which invariably need salt for their growth and metabolism, and facultative halophytes, which grow and adapt to saline as well as nonsaline conditions. Halophytes are also divided based on their occurrence with respect to water, i.e., hydro-halophytes, which grow in saline water medium, and xero-halophytes which grow mainly in dry land saline conditions.

Majority of the halophytes are deep-rooting perennials that achieve their optimum growth and yield potential at thresholds between 6 and 25 dS m^{-1} (EC), levels at which virtually all of our modern crops would perish. Some of the more prolific ones thrive in the coastal saline soils and arid inland saline areas with concentrations of 45 dS m^{-1} (seawater) and above, e.g., *Salvadora persica.* With their vigorous growth and root development, these plants are often able to take advantage of less saline moisture within the soil profile and adapt to seasonal variability in salinity by altering germination, growth, and reproduction cycles to best suit their survival needs.

In general, halophytes produce *by and large* salt-free seeds which require freshwater for proper germination. However, there are exceptions among the extreme ones which are able to germinate even at half the concentration of seawater, e.g., *Salvadora persica* (Rao et al. 2003, 2004, 2012). As they grow into seedlings and mature, halophytes begin to develop and exhibit the salt-tolerance mechanisms for which they are known. In certain halophyte species, distinct life cycle variations in salt tolerance have been observed which include increased sensitivity when a plant is producing seed or forming buds. Once established, halophytic perennials are better able to retain moisture in the root zone than shallow-rooting annual crops. Although well adapted to sandy well-drained soils, persistent root penetration also enables them to perform in clayey soils.

In recent years, however, the attention is being paid worldwide to accommodate the salt-tolerant species of industrial importance for highly saline degraded areas including coastal marshes. Some oil-yielding species such as *Salicornia bigelovii*, *Salvadora persica*, *S. oleiodes*, *Terminalia catappa*, *Calophyllum inophyllum*, and species of *Pandanus* are important and can be grown in highly saline areas irrigating with seawater or water of high salinity. *Borassus flabellifer*, *Calophyllum inophyllum*, *Pongamia pinnata*, and *Nypa fruticans* are other important coastal plants of economic importance. Similarly many inland salt-tolerant species find industrial application. The petro-crops like *Jatropha curcas and Euphorbia antisyphilitica* can successfully be grown irrigating with water of high salinity. *Capparis decidua* found in saline arid regions is highly medicinal and valued for commercial pickle. *Simmondsia chinensis* with seed oil similar to that of sperm whale; aromatic species like *Matricaria chamomilla*, *Vetiveria zizanioides*, *Cymbopogon martinii*, *and C. flexuosus*; and medicinal plants such as Isabgol (*Plantago ovata*), *Adhatoda vasica*, *Withania somnifera*, *Cassia angustifolia*, *and* many others can be grown successfully on alkali soil (up to pH 9.6) as well as calcareous saline soil irrigating with saline water up to EC 12 dS/m (Dagar 2005). From coastal Gujarat, many halophyte species have been identified that are economically useful and can be successfully used for effective phytoremediation of saline soils (Arora et al. 2013).

Halophytes (e.g., *Crithmum maritimum*, *Portulaca oleracea*, *Salicornia* spp., and *Aster tripolium*) have been consumed by humans for centuries and to date are still often gathered from the coastal salt marshes and inland salt pans of Europe (Tardio et al. 2006). These species are well known for their ability to synthesize secondary metabolites, which have several functions, such as osmolytes and scavengers of reactive oxygen species (Hasegawa et al. 2000). The secondary metabolites include simple and complex sugars, amino acids, quaternary ammonium compounds, polyols, and antioxidants (e.g., polyphenols, β-carotene, ascorbic acid, and ureides; Parvaiz and Satyawati 2008; Ventura and Sagi 2013). Osmolytes can potentially be utilized in functional food, which is defined as having disease-preventing and/or health-promoting benefits (Buhmann and Papenbrock 2013). Several halophyte products such as *Salicornia* spp. and *Aster tripolium* are already being sold as sea vegetables and salad crops in the European markets at comparatively high prices (Böer 2006). A number of additional halophytes, e.g., *Salsola soda*, *Crambe maritima*, and *Beta maritima*, have a great potential to be released as novel sea vegetables to the market. The nonseasonality and year-round availability was an important step in the dissemination of the *Salicornia* crop and should be realized for any further halophyte vegetable (Böer 2006).

There are also many other salt-tolerant fruit, forage, oil-yielding, medicinal, and fuelwood species, which have been tried and found suitable for highly saline situations. The scopes of many of these species of high economic value for saline and sodic habitats along with their management and utilization have been discussed in this paper.

3 Halophytes and Saline Lands

3.1 India Scenario

A sizeable portion of the salt-affected soils are highly deteriorated making rehabilitation of such lands difficult due to lack of resources, such lands being community lands and being owned by resource-poor farmers using costly chemical amendments. Revegetation of such lands through different land uses, viz., plantation of multipurpose tree species including energy plantation as one of the options to meet the fuel, fodder, timber, and energy needs, is promising in view of fuelwood, energy, fodder shortages, and environmental benefits. This approach is known to have the potential to reclaim wastelands and provide livelihood security through regular employment generation. Due to large population, India cannot afford any diversion of agricultural land to meet its fast-rising energy demands which have to be met from such marginal areas only.

3.2 Scenario in Coastal Gujarat

The total salt-affected soil in India was reported approx. about 6.727 Mha out of which 3.2 Mha is coastal soil, 2.8 Mha is sodic land, and the rest is inland saline soil. Gujarat with 2.2 Mha contributes to 20 % of the total salt-affected soil in the country. Gujarat comes second after West Bengal in the total extent of coastal salt-affected soil with estimated area of about 7.2 lakh hectare. This 7.2 lakh hectare is distributed in the district of Kutch, Saurashtra region, and districts of South Gujarat.

The wide variety of halophytes and of their characters permits to envision a profitable use of vast barren extensions of saline lands by selecting the appropriate species best fitting local conditions. Possible actions in dependence of peculiar soil and water conditions are synthetically shown in Table 1.

Table 1 Possible actions for coastal and inland saline lands

Case	Soil	Main water source	Principal possible actions
1	Coastal lands	Seawater	Fixing dunes, landscaping, growing mangroves, fodder production
2	Inland saline areas	Brackish/saline water	Various scopes
3	Inland saline areas (dry)	Rain	Erosion control, fodder production
4	Salinized agricultural lands	Fresh/brackish water	Soil rehabilitation, agricultural production
5	Endangered agricultural lands	Fresh/brackish water	Soil protection, agricultural production

All the possible actions listed in the table can be easily undertaken after an appropriate plant selection, but a preliminary analysis assessing their environmental, economic, and social feasibility is in all cases required.

4 Salt Tolerance of Halophytes

Salinity is an abnormal growth condition and thus perceived as a stress in glycophytes, whereas for halophytes, it seems more appropriate to describe salinity as normal and more of a constraint. Halophytes have evolved to manage and adapt to these constraints, employing a number of physiological mechanisms (biochemical and morphological) that enable them to tolerate the elevated concentrations of sodium and chloride in soil. Although there are many aspects of the physiology of salt tolerance that are yet to be understood, it is clear that the trait is complex in that, at a minimum, it requires the combination of several different traits: the accumulation and compartmentation of ions for osmotic adjustment, the synthesis of compatible solutes, the ability to accumulate essential nutrients (particularly K) in the presence of high concentrations of the ions generating salinity (Na), the ability to limit the entry of these saline ions into the transpiration stream, and the ability to continue to regulate transpiration in the presence of high concentrations of Na^+ and Cl^- (Flowers and Colmer 2008).

4.1 K/Na Selectivity

The selectivity of halophytes for K over Na varies between families of flowering plants (Flowers et al. 1986). Net selectivity (net $S_{K:Na}$) calculated as the ratio of K concentration in the plant to that in the medium divided by the ratio of Na concentration in the plant to that in the medium, ranges between average values of 9 and 60 (Flowers and Colmer 2008) with an overall mean of 19; it is only in the Poales that net $S_{K:Na}$ values of the order of 60 are found. Within the monocots, there are three orders with halophytes, but no data are available for the net $S_{K:Na}$ values of species within the Arecales. In the Alismatales, the average net $S_{K:Na}$ (across just three species) is 16 (range 10–22), suggesting that high selectivity has evolved only in the Poales (for halophytes within this order, average selectivities are 58 in the Juncaginaceae (two species) and 60 in the Poaceae (nine species). There is too little data to analyze the net $S_{K:Na}$ values within the dicots, but the average value is 11 compared with 60 in the Poales (Flowers and Colmer 2008).

4.1.1 Salt Compartmentation

Distribution of sodium and chloride ions (Fig. 1) studied in different plant parts of *S. persica* growing at different in situ salinities indicated bark and senescing leaves

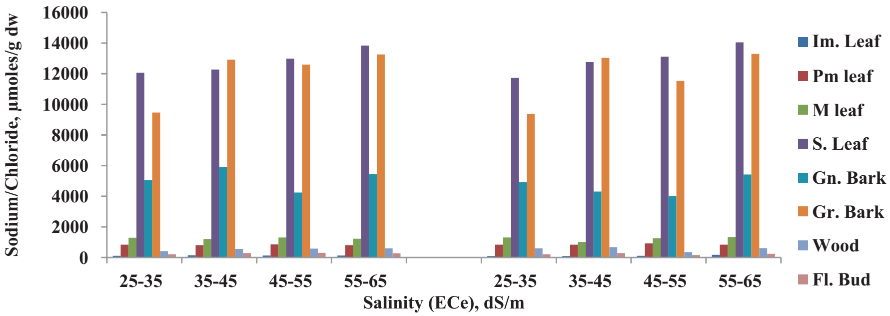

Fig. 1 Na and Cl compartmentation in *S. persica*

as the potential sinks for such toxic ions, thereby sparing other plant parts like immature leaves, partially mature and physiologically mature leaves to perform their normal physiological activity and help in normal growth and development, which enable the plants to remain lush green even at high salinity. Further, senescing leaves act as potential sinks for toxic ions thereby reducing the load on other photosynthesizing tissues, which remain by and large salt-free (Rao et al. 2003).

4.1.2 Na^+ and Cl^- Concentration and Flux

The rate and ion transport (flux) from root to shoot and to whole plant was calculated using the formula, Js = (Ms2 − Ms1) ln (WR2/WR10/(t2 − t1)(9WR2 − WR1), where Js is the rate of transport (flux), Ms1 and Ms2 are the amounts of ion in the shoot/whole plant, and WR1 and WR2 are the fresh weights of the roots at the harvest times t2 and t1 (Pitman 1975). Concentration of sodium and chloride in plant parts increased with increase in salinity of the soil. Maximum amount of Na^+ and Cl^- ions was retained in the bark, root, and senescing leaves sparing immature (expanding) and mature (fully expanded) leaves over the years (Table 2). These tissues act as potential sink for excess sodium and chloride ions. The capacity of the sink increased with age of the plant as well as increase in salinity which indicates that *S. persica* has very well developed salt compartmentation mechanism (Rao et al. 2004). Though Na^+ concentration increases with increase in salinity, the total Na uptake showed a decreasing trend which may be obviously due to decrease in the biomass yield with increase in salinity. Similarly, chloride uptake in root is much higher than that of the shoot (Table 3). The rate of flux of Na^+ and Cl^- ions to the whole plant while increase with increase in salinity showed a decreasing trend with age (Table 4). The flux of these ions from root to the shoot was a fraction of that to the whole plant indicating that roots accumulate more ions than shoots. In this species, roots act as both Na^+ and Cl^- accumulator.

Table 2 Concentration of Na^+ and Cl^- (%) ions in different plant parts of *Salvadora persica* grown on saline black soils

Plant part	Salinity range (dS m^{-1})											
	25–35			35–45			45–55			55–65		
	2nd year	3rd year	4th year	2nd year	3rd year	4th year	2nd year	3rd year	4th year	2nd year	3rd year	4th year
Na^+												
Root	1.13	1.62	1.86	1.61	2.11	2.30	1.91	2.37	2.57	1.93	2.39	2.60
Wood	0.02	0.03	0.03	0.03	0.04	0.04	0.03	0.04	0.05	0.04	0.06	0.06
Bark	1.59	1.72	1.95	2.12	2.29	2.60	2.33	2.52	2.86	2.73	2.95	3.34
Im. leaf	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03
M. leaf	0.18	0.18	0.21	0.19	0.20	0.23	0.21	0.22	0.25	0.22	0.24	0.27
S. leaf	1.66	1.81	2.06	2.11	2.30	2.61	2.30	2.38	2.71	2.39	2.51	2.83
CD 0.05	0.36	0.13	0.18	0.46	0.21	0.22	0.89	0.16	0.30	0.69	0.46	0.71
Cl^-												
Root	2.13	2.65	2.70	2.65	3.36	3.60	2.88	3.00	3.90	2.94	4.00	4.01
Wood	0.04	0.05	0.06	0.05	0.06	0.06	0.05	0.07	0.07	0.07	1.00	0.10
Bark	2.49	2.69	3.05	3.43	3.70	4.01	3.74	4.04	4.41	4.26	4.62	5.14
Im. leaf	0.03	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.5	0.05	0.06
M. leaf	0.28	0.29	0.32	0.31	0.31	0.38	0.33	0.34	0.39	0.35	0.40	0.42
S. leaf	2.63	2.82	3.19	3.17	3.67	2.71	3.58	3.76	4.23	3.58	4.04	4.59
$CD_{0.05}$	0.40	0.16	0.39	1.05	0.28	0.30	0.58	0.22	0.40	0.95	0.98	0.83

4.1.3 Ion Compartmentation in Halophytic Grasses

Ion compartmentation at organ level indicated higher amount of sodium in roots followed by stem and old leaves and the least in inflorescence in both the grasses. Similar trend was observed in potassium in that foliage and roots had higher potassium than inflorescence (Table 5). Higher accumulation of sodium in roots, old leaves, and stems indicates the physiologically mature foliage had relatively low tissue sodium. Of the two forage grasses, *Aeluropus* had higher potassium in foliage, while *Eragrostis* had higher potassium in roots. Contrary to this, sodium was found to be more in the foliage of *Eragrostis*, while roots of *Aeluropus* had marginally higher sodium. Once the flowering occurs, higher sodium is found to be more in older leaves in *Eragrostis*, compared to *Aeluropus*, while older leaves showed lesser sodium when compared to shoot (Rao et al. 2011).

4.2 Salt Glands

Excretion is perhaps the most readily observable self-regulating behavior. This adjustment is often characterized by the secretion of salty sap through epidermal pores, glands, and bladders located on the plant's roots, shoots, and leaves.

Table 3 Uptake of Na^+ and Cl^- ions in *S. persica* on saline black soils

Salinity class (dS m^{-1})	Uptake (g)			
	Shoot		Root	
	Na^+	Cl^-	Na^+	Cl^-
	2nd year			
25–35	6.44	10.18	8.40	15.86
35–45	5.12	8.53	9.31	15.29
45–55	4.10	6.57	6.58	9.91
55–65	3.68	5.64	4.97	7.56
$CD_{0.05}$	1.21	1.88	1.93	2.12
	3rd year			
25–35	16.01	25.90	27.36	44.93
35–45	14.21	22.95	27.69	44.08
45–55	10.13	16.21	18.56	29.43
55–65	9.82	15.59	13.62	22.84
$CD_{0.05}$	2.11	2.88	3.58	5.35
	4th year			
25–35	22.31	34.71	38.33	56.66
35–45	18.42	28.69	37.64	58.73
45–55	14.43	22.30	37.23	37.23
55–65	13.51	20.84	29.35	29.35
$CD_{0.05}$	3.95	4.23	0.53	1.88

Table 4 Flux of Na^+ and Cl^- ions in *S. persica* on saline black soils

Salinity class, dS m^{-1}	Flux (μg g^{-1} day^{-1})			
	Shoot		Root	
	Na^+	Cl^-	Na^+	Cl^-
	Between 3rd and 2nd year			
25–35	29.9	46.1	9.8	16.2
35–45	39.0	61.3	12.9	20.4
45–55	50.2	81.3	16.8	26.9
55–65	78.8	131.4	19.5	52.6
$CD_{0.05}$	10.5	13.8	4.3	5.8
	Between 4th and 3rd year			
25–35	10.8	12.9	3.9	5.5
35–45	12.3	17.8	3.7	5.0
45–55	17.8	23.5	7.3	9.7
55–65	29.7	410.2	11.9	16.9
$CD_{0.05}$	1.88	3.50	1.20	1.70

Table 5 Ion compartmentation in halophytic grasses (mmoles g^{-1} dry weight)

	Aeluropus lagopoides			*Eragrostis* spp.		
Plant part	Na^+	K^+	Na/K	Na^+	K^+	Na/K
Inflorescence	2.6	4.4	0.590	4.3	4.9	0.876
Mature foliage	9.2	8.8	1.409	11.6	7.6	1.526
Stem	16.1	10.4	1.548	12.4	7.9	1.570
Old leaves	13.6	7.9	1.722	14.2	7.4	1.972
Root	30.2	8.8	3.432	29.4	9.1	3.231

Intercellular transport mechanisms (pumps) move excess salt ions from surface cells to the outside of the leaf or stem leaving visible crystal deposits once the water has evaporated. The more highly evolved halophytic grasses, shrubs, and trees employ this device regularly in order to desalinate internal fluids by excreting sodium and chloride ions at critical periods in their development.

Glandular structures are not uncommon on plants; they can secrete a range of organic compounds. However, the ability to secrete salt appears to have evolved less frequently than salt tolerance. Salt glands, epidermal appendages of one to a few cells that secrete salt to the exterior of a plant (Thomson et al. 1988), have been described in just a few orders of flowering plants – the Poales (e.g., in *Aeluropus littoralis* and *Chloris gayana*), Myrtales (e.g., the mangrove *Laguncularia racemosa*), Caryophyllales (e.g., *Mesembryanthemum crystallinum* and the saltbush *Atriplex halimus*), Lamiales (e.g., the mangroves *Avicennia marina* and *Avicennia germinans*), and the Solanales (e.g., *Cressa cretica*). Their distribution across the orders of flowering plants suggests at least three origins, although there may have been more independent origins within orders. Whether salt glands evolved from glands that originally performed some other function is unclear, but it is difficult, at least in the Poaceae, to get glandular hairs on non-halophytes (such *as Zea mays* L.) to secrete salt.

5 Importance of Halophytes

5.1 Agriculture and Land Management

Salt-affected lands are increasing worldwide through vegetation clearance and irrigation, both of which raise the water table bringing dissolved salts to the surface. It is estimated that up to half of irrigation schemes worldwide are affected by salinity (Flowers and Yeo 1995). Although irrigated land is a relatively small proportion of the total global area of food production, it produces a third of the food (Munns and Tester 2008). Salt stress has been identified as one of the most serious environmental factors limiting the productivity of crop plants (Flowers and Yeo 1995), with a huge impact on agricultural productivity. The global annual cost of salt-affected land is likely to be well over US$12 billion (Qadir et al. 2008). Future agricultural production will rely increasingly on our ability to grow food and fiber plants in salt-affected land (Rozema and Flowers 2008; Qadir et al. 2008).

5.2 Halophytes as Crops

Naturally salt-tolerant species are now being promoted in agriculture, particularly to provide forage, medicinal plants, aromatic plants (Qadir et al. 2008), and for forestry. Examples of useful halophytes include the potential oilseed crops *Kosteletzkya virginica*, *Salvadora persica*, *Salicornia bigelovii*, and *Batis maritima*; fodder crops such as *Atriplex* spp. and *Distichlis palmeri*; and biofuels. Growing salt-tolerant biofuel crops on marginal agricultural land would help to counter concerns that the biofuel industry reduces the amount of land available for food production (Qadir et al. 2008). At the extreme, plants that can grow productively at very high salt levels could be irrigated with brackish water or seawater (Rozema and Flowers 2008). Although plants that put resources (Yeo 1983) into developing salt-tolerance mechanisms (e.g., the production of compatible solutes to maintain osmotic balance is an energetic cost) may do so at the expense of other functions, many halophytes show optimal growth in saline conditions (Flowers and Colmer 2008) and salt marshes have high productivity. The fact that dicotyledonous halophytes can grow at similar rates to glycophytes suggests that salt tolerance per se will not limit productivity. Here the contrast with drought tolerance is stark: without water, plants do not grow but may survive; with salt water, some plants can grow well. Apart from direct use as crops, we may increasingly need to rely on halophytes for revegetation and remediation of salt-affected land. Over the last 200 years, industrialization in Europe and elsewhere has led to an enormous increase of production, use, and release of traces of heavy metals into the environment. A large portion of these toxic materials, including Cd, Cu, Pb, and Zn, accumulate in sediments, including the soils of tidal marshes. Recent studies showed that some sea grasses and salt marsh plants are capable of extracting heavy metals from sediments and accumulating them in belowground or aboveground tissues (Weis and Weis 2004). The processes and potential application of these aquatic halophytes merits much greater research and development. Growing salt-tolerant plants, including species of *Kochia*, *Bassia*, *Cynodon*, *Medicago*, *Portulaca*, *Sesbania*, and *Brachiaria*, may also improve other soil properties, such as increasing water conductance or increasing soil fertility (Qadir et al. 2008). Halophytes may also lower the water table, thereby allowing growth of salt sensitive species in salt-affected land.

5.3 Food-Yielding Halophyte and Salt-Tolerant Plants

Among conventional crops, beetroot (*Beta vulgaris*) and date palm (*Phoenix dactylifera*) are well known for their food value, and these can be grown successfully irrigating with saline water. Fruit-bearing gooseberry (*Emblica officinalis*), karonda (*Carissa carandas*), ber (*Ziziphus mauritiana*), and bael (*Aegle marmelos*) withstand drought as well as salinity. These can be cultivated with success irrigating with water up to 12 dS/m. These along with guava (*Psidium guajava*) and *Syzygium cumini* could be grown on highly alkali soil (pH up to 9.8) with application of amendments (gypsum) in auger holes. Pomegranate (*Punica granatum*) is salt tolerant but does not withstand waterlogging. This when grown on raised bunds in alkali soil (pH 10) performed well along with kallar grass (*Leptochloa fusca*), a forage grass producing 15–20 Mg/ha fresh forage, and rice (var. CSR-10) producing up to 4 Mg/ha grains when grown in sunken beds without applying any amendments. Raw fruits of kair (*Capparis decidu*a) are used for pickles and possess medicinal value. It grows naturally on both saline and sodic soils and can be cultivated raising from rootstocks, seeds, and also stem cuttings in nursery and then transplanting. It may be irrigated with saline water. The coastal badam (*Terminalia catappa*) and species of *Pandanus* are known for their oils of industrial application. Fruits of Pandanus are staple food for coastal population of bay and islands, and both of these plants are found naturally growing in tidal zone. These can be cultivated successfully in coastal areas. Palmyra palm (*Borassus flabellifer*) is widely used for toddy, jaggery, vinegar, beverage, juice for sugar, and as edible radicles and fruits and is found widely distributed all along Andhra coast. It needs to be genetically improved for wider cultivation. The use of this in paper industry in Rajasthan and Gujarat is well known. The young leaves and shoots of *Chenopodium album*, species of *Amaranthus*, *Portulaca oleracea*, *Sesuvium portulacastrum*, and many others are used as vegetable and salad in many parts of the country. Many of these are even cultivated (Dagar 2005).

5.4 Forages

In the past, halophytic grasses, shrubs, and trees, containing digestible protein levels comparable to conventional livestock feed, were planted as forage or harvested for fodder. In spite of their recent decline, forage and fodder still account for the bulk of commercial halophyte cultivation around the world: these include grasses (*Distichlis*, *Paspalum*, *Spartina*, *Sporobolus*, *Aeluropus*, *and Eragrostis)*, shrubs *(Atriplex*, *Salsola*, and *Suaeda*), and trees (*Acacia*, *Cassia*, *Leucaena*, and *Prosopis*). Halophytic grasses could help millions of small farmers whose farms are affected by salinity. By growing these grasses as an animal feed crop, these farmers could maintain the productivity of their farms with water that become increasingly brackish or saline. Due to the relatively high salt content in their tissue (between 10 and 50 % of their dry weight), the potential is greatest when interplanted with native forage or used in mixed feeding regimes as a dry season browse and fodder supplement. Certain nitrogen-fixing halophytes (*Albizia*, *Cassia*, *Cyamopsis*, *Leucaena*, *Pongamia*, *Sesbania*, and *Trifolium*) have been effectively utilized as cover crops, green manure, mulch, and compost.

In many coastal areas where mangroves occur sporadically and there is scarcity of fodder, the foliage of many mangrove and associated plants, such as species of *Avicennia*, *Ceriops*, *Rhizophora*, *Terminalia*, *Pongamia*, and others, is used as forage for cattle, goats, and camel. Among other trees, species of *Acacia*, *Prosopis*, *Salvadora*, *Cordia*, *Ailanthus*, *and Ziziphus* are traditional fodder plants of arid regions. Species of *Salicornia, Chenopodium*, *Kochia, Atriplex, Salsola, Suaeda, Trianthema, Portulaca, Tribulus, and Alhagi* along with several grasses such as *Leptochloa fusca*, *Aeluropus lagopoides*, *Cynodon dactylon*, *Dactyloctenium sindicum*, *Paspalum vaginatum*, *Sporobolus airoides*, *S. marginatus*, *Chloris gayana*, *Echinochloa turnerana*, *E. colonum*, *Eragrostis tanella*, *Dichanthium annulatum*, *D. caricosum*, *Brachiaria mutica*, *Bothriochloa pertusa*, and many others are commonly used as forages from alkali and saline areas. Many of these forages can be cultivated successfully on degraded salt-affected soils or in drought prone areas irrigating with saline water, where other arable crops cannot be grown. In inland sodic lands, intercropping in *Jatropha curcas* have ameliorative effect (Singh et al. 2016).

5.5 Industrial Oil Production

Salinity and alkalinity are the two most important factors limiting agricultural productivity in arid and semiarid regions. Reclaiming these lands for commercial crops is too costly for most countries to afford. Faced with a declining base of arable farmland and increasing demand for food, fiber, and energy, this warrants the need for utilization of naturally salt-tolerant species (halophytes) in irrigated and nonirrigated agriculture. *Salvadora persica*, a facultative halophyte, appears to be a potentially valuable oilseed crop for saline and alkali soils, since the seed contains 40–45 % of oil rich in industrially important lauric (C_{12}) and myrestic (C_{14}) acids. Attempts were made to assess the performance of the species on saline and alkali soils. From the results, it was evident that the species can be grown on both soil types; however, height, spread, and seed yield were significantly higher for plants grown on saline soils as compared to plants cultivated on alkali soils. No significant difference was observed in oil content between seed obtained from plants grown on saline and alkali soils. The study indicated that *S. persica* can be cultivated as a source of industrial oil on both saline and alkali soils for economic and ecological benefits, otherwise not suitable for conventional arable farming (Reddy et al. 2008). Recently, *Salicornia bigelovii* has been evaluated as a source of vegetable oil and the cake as animal feed and is being grown in some areas of Gujarat and Rajasthan. It withstands high salinity both of soil and water.

Salicornia bigelovii has been evaluated as a source of vegetable oil and the cake as animal feed, is being grown in some areas of Gujarat and Rajasthan. It withstands high salinity both of soil and water (Dagar 2005). Several studies have shown that the oilseed halophyte *Salicornia* irrigated with seawater displayed high seed and biomass production (Pandya et al. 2006). Similar results were also reported for *Cakile maritima*, also a halophyte.

6 Phytoremediation

Phytoremediation is the cultivation of plant for the purpose of reducing soil and water contamination (by organic and inorganic pollutants) that result from improper disposal of aquaculture, agriculture, and industrial effluent. On salt-affected soil, phytoremediation is often an effective and economical method of removing or reducing contaminates. Phytoremediation of salt affected soils through halophytes can be a cost-effective and environmentally sound technology for remediation of saline as well as sodic soils, if it can be properly developed. Although there are some limitations in the plant based remediation system, like phytoremediation is time-consuming for allowing plants to grow for several seasons. Also through plants, depending on the root system, limited soil depths can be reclaimed (USEPA 2000). For successful remediation of salt laden soils, salt-tolerant plants or halophytes with deep and vigorous root growth, as well as sufficient above-ground biomass production, is one of the basic criteria for the selection of plants for remediation. In alkali soils, salt tolerant multipurpose plants species including biofuel and grass species can help in bio-amelioration of degraded agricultural and wastelands (Singh et al. 2011, 2016). Phytoremediation with trees and grasses is beneficial because these can be utilized as fodder, timber, and fuel (Hasanuzzaman et al. 2014). *Salicornia* cultivation may also confer economic benefits as the plants can be harvested for selenium-rich animal feed. A number of halophytic grasses have been proven to be effective in revegetating brine-contaminated soil that typically results from gas and oil mining.

7 Environmental Conservation

Halophytes are especially well suited for using brackish/saline water often requiring little or no freshwater in order to rehabilitate degraded vegetative habitats. For many, the application of both fresh and saline waters in mixed or alternating irrigation programs can provide appreciable cost reductions and resource savings. Integrated resource management schemes and the multiple use of drainage water for increasing salt-tolerant crops can significantly reduce on-farm consumption and replenish freshwater reservoirs. With proper management and waste disposal, these schemes can also prevent the further salinization of aquifers and groundwater of surrounding lands and habitats. Under waterlogged conditions, halophytes have demonstrated the ability to reduce saline water tables and, to a certain extent, reclaim affected lands. These deep-rooting trees and shrubs, with their continuous demand for water, help manage salinity and moisture in the upper soil layers and tend to drive salts below the root zone of most other plants.

8 Carbon Sequestration

All plants extract carbon dioxide from the atmosphere for photosynthesis and biomass production. In general, halophyte biomass yields are comparable to those of glycophytes, yet the associated costs of cultivation are often far less particularly in areas where there is an overabundance of saline resources. Halophytic agroforestry plantations may represent a cost-effective option for sequestering carbon and reducing their elevated levels in the biosphere. While trying to determine if indeed halophytes can be effectively utilized as carbon sinks, their potential for meeting our more immediate needs for crop alternatives and environmental conservation could be adequately assessed.

It can be concluded that some economically useful halophytes can be effective in bio-amelioration of salt affected lands as these plants having capability to remove substantial quantities of salts by producing higher biomass thereby improving the soils.

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Microbial Approach for Bioremediation of Saline and Sodic Soils

Sanjay Arora and Meghna Vanza

1 Introduction

Both physical and chemical methods for saline/sodic soil reclamation are not cost-effective. The biotic approach 'plant-microbe interaction' to overcome salt stress has recently received a considerable attention from many workers throughout the world. Plant-microbe interaction is a beneficial association between plants and microorganisms and also a more efficient method used for the reclamation of salt-affected soils. Bacteria are the most commonly used microbes in this technique. Rhizosphere bacteria improve the uptake of nutrients by plants and/or produce plant growth-promoting compounds and regenerate the quality of soil. These plant growth-promoting bacteria can directly or indirectly affect plant growth. Indirect plant growth promotion includes the prevention of the deleterious effects of phytopathogenic organisms by inducing cell wall structural modifications and biochemical and physiological changes leading to the synthesis of proteins and chemicals involved in plant defence mechanisms.

2 Halophilic Microbes

The existence of high osmotic pressure, ion toxicity, unfavourable soil physical conditions and/or soil flooding is a serious constraint to many organisms, and therefore salt-affected ecosystems are specialized ecotones. The organisms found over there

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have developed mechanisms to survive in such adverse media, and many endemisms. The halophilic microorganisms or 'salt-loving' microorganisms live in environments with high salt concentration that would kill most other microbes. Halotolerant and halophilic microorganisms can grow in hypersaline environments, but only halophiles specifically require at least 0.2 M of salt for their growth. Halotolerant microorganisms can only tolerate media containing <0.2 M of salt. Distinctions between different kinds of halophilic microorganisms are made on the basis of their level of salt requirement and salt tolerance.

According to Kushner (1993) classification of microbes' response to salt in which they grow best, five groups were defined.

1. Non-halophilic, <0.2 M (~1 %) salt
2. Slight halophiles, 0.2–0.5 M (~1–3 %) salt
3. Moderate halophiles, 0.5–2.5 M (~3–15 %) salt
4. Borderline extreme halophiles, 1.5–4.0 M (~9–23 %) salt
5. Extreme halophiles, 2.5–5.2 M (~15–32 %) salt

The halotolerant microorganisms grow best in media containing <0.2 M (~1 %) salt and also can tolerate high salt concentrations. This definition is widely referred to in many reports (Arahal and Ventosa 2002; Ventosa et al. 1998; Yoon et al. 2003).

2.1 Halophilic Soil Bacteria

The soil is an important habitat for bacteria. Soil bacteria can be found as single cells or as microcolonies, embedded in a matrix of polysaccharides. Bacteria inhabiting the soil play a role in conservation and restoration biology of higher organisms. The domain bacteria contain many types of halophilic and halotolerant microorganisms, spread over a large number of phylogenetic groups (Ventosa et al. 1998). The different branches of the *Proteobacteria* contain halophilic representatives often having close relatives that are non-halophilic. Similarly, halophiles are also found among the *Cyanobacteria* (Oren 2002), the *Flavobacterium-Cytophaga* branch, the *Spirochetes* and the *Actinomycetes*. Within the lineages of Gram-positive bacteria (*Firmicutes*), halophiles are found both within the aerobic branches (*Bacillus* and related organisms) as also within the anaerobic branches.

In general, it may be stated that most halophiles within the domain bacteria are moderate rather than extreme halophiles. However, there are a few types that resemble the archaeal halophiles of the family *Halobacteriaceae* in their salt requirements and tolerance.

Rodriguez-Valera (1988) stated that there was an abundance of halophilic bacteria in saline soil and that the dominant types encountered in saline soil belong to genera of *Alcaligenes*, *Bacillus*, *Micrococcus* and *Pseudomonas*. Garabito et al. (1998) isolated and studied 71 halotolerant Gram-positive endospore-forming rods from saline soils and sediments of salterns located in different areas of Spain. These isolates were tentatively assigned to the genus *Bacillus*, and the majority of them were classified as extremely halotolerant microorganisms, being able to grow in most cases in up to 20 or 25 % salts.

2.2 Moderately Halophilic Bacteria

Several alkaliphilic *Bacillus* species that have been isolated from soils showed halophilic characteristics. *Bacillus krulwichiae*, a facultatively anaerobic (Yumoto et al. 2003), isolated in Tsukuba, Japan, is a straight rod with peritrichous flagella that produces ellipsoidal spores (Table 1). These have ability to utilize benzoate or *m*-hydroxybenzoate as the sole carbon source. *Bacillus patagoniensis* (Olivera et al. 2005) was isolated from the rhizosphere of the perennial shrub *Atriplex lampa* in north-eastern Patagonia. Another is *Bacillus oshimensis* (Yumoto et al. 2005). It is a halophilic nonmotile, facultatively alkaliphilic species. Another example is the genus *Virgibacillus*. This genus comprises eight species, two of which are moderately halophilic and have been isolated from soil samples: *Virgibacillus salexigens* (Heyrman et al. 2003) and the recently described *Virgibacillus koreensis* (Lee et al. 2006).

Several other aerobic or facultatively anaerobic, moderately halophilic, endospore-forming, Gram-positive bacteria have been classified within genera related to *Bacillus*. Genera that include halophilic species isolated from soil samples are *Halobacillus*, *Filobacillus*, *Tenuibacillus*, *Lentibacillus* and *Thalassobacillus*. Species from *Filobacillus*, *Thalassobacillus* and *Tenuibacillus* genera are borderline halophile.

Table 1 Isolation of moderate halophile species from different sources

Sr. No	Species	Gram's nature	Isolation source	Reference
1	*Bacillus krulwichiae*	P	Soil from Tsukuba, Ibaraki, Japan	Yumoto et al. (2003)
2	*Bacillus haloalkaliphilus*	P	Showa, Saitama	Echigo et al. (2005)
3	*Bacillus oshimensis*	P	Soil from Oshamanbe, Oshima, Hokkaido, Japan	Yumoto et al. (2003)
4	*Bacillus patagoniensis*	P	Rhizosphere of the perennial shrub *Atriplex lampa* in north-eastern Patagonia, Argentina	Olivera et al. (2005)
5	*Gracilibacillus halotolerans*	P	Shiki, Saitama	Echigo et al. (2005)
6	*Halobacillus halophilus*	P	Salt marsh and saline soils	Spring et al. (1996), Ventosa et al. (1983)
7	*Halobacillus karajensis*	P	Saline soil of the Karaj region, Iran	Amoozegar et al. (2003)
8	*Halomonas anticariensis*	N	Soil from Fuente de Piedra, Málaga, Spain	Martínez-Cánovas et al. (2004)
9	*Halomonas boliviensis*	N	Soil around the lake Laguna Colorada, Bolivia	Quillaguaman et al. (2004)
10	*Halomonas maura*	N	Soil from a solar saltern at Asilah, Morocco	Bouchotroch et al. (2001)
11	*Halomonas organivorans*	N	Saline soil from Isla Cristina, Huelva, Spain	Garcia et al. (2004)

The genus *Halobacillus* is clearly differentiated from other related genera on the basis of its cell wall peptidoglycan type. Within these genera, the halophilic species isolated from soils are *Halobacillus halophilus* (Spring et al. 1996) and *Halobacillus karajensis* (Amoozegar et al. 2003). With respect to the genus *Lentibacillus*, two halophilic soil species are identified: a *Lentibacillus salicampi* isolated from a salt field in Korea (Yoon et al. 2002) and a *Lentibacillus salarius* from a saline sediment in China (Jeon et al. 2005).

The family *Nocardiopsaceae* contains three genera, namely, *Nocardiopsis* (Meyer 1976), *Thermobifida* (Zhang et al. 1998) and *Streptomonospora* (Cui et al. 2001). Some examples of moderately halophilic species of the genus *Nocardiopsis* isolated from soil samples are *Nocardiopsis gilva*, *Nocardiopsis rosea*, *Nocardiopsis rhodophaea*, *Nocardiopsis chromatogenes*, and *Nocardiopsis baichengensis* (Li et al. 2006). These all are isolated from saline sediment from Xinjiang Province, China. From salt pans of Kovalam in Kanyakumari district of Kerala, India, Gram-negative moderately halophilic bacteria like *Natranobacterium sp-1* were identified in the study of the diversity over period of time. Many Gram-negative, moderately halophilic or halotolerant species are currently included in the family *Halomonadaceae*. This family includes three genera with halophilic species: *Halomonas*, *Chromohalobacter* and *Cobetia*. Among the genera that comprise this family, *Halomonas* covers the greatest number of species (more than 40) showing heterogeneous features. Some species were isolated from soil samples: *Halomonas organivorans*, originating from saline soil samples in Spain, and *Halomonas boliviensis* (Quillaguaman et al. 2004) were described as alkaliphilic and alkalitolerant moderately halophilic bacteria, respectively, in as much as these bacteria are able to grow in media with pH values of about 8–9. From coastal saline soils of Gujarat, halophilic *Rhizobium* species were isolated from the rhizosphere of salt tolerant legume plants (Trivedi and Arora 2013).

The genus *Marinobacter*, with the type species *Marinobacter hydrocarbonoclasticus*, was created in 1992 to accommodate Gram-negative, moderately halophilic, aerobic *Gammaproteobacteria* that utilize a variety of hydrocarbons as the sole source of carbon and energy (Gauthier et al. 1992). They also accommodate moderately halophilic *Marinococcus halophilus* and *Marinococcus albus* (Hao et al. 1984). Li et al. (2005) described a third species, *Marinococcus halotolerans*, which is extremely halophilic. They are motile cocci that grow over a wide range of salt concentrations and up to 20 % NaCl.

Yeasts and other fungi are chemoheterotrophic cell-walled eukaryotes, some of which are well adapted to tolerate hypersaline environments. They grow best under aerobic conditions on carbohydrates at moderate temperatures and acidic to neutral pH. *Debaryomyces hansenii* is a halotolerant yeast, isolated from sea water, which can grow aerobically up to salinities of 4.5 mol/L NaCl. It produces glycerol as a compatible solute during the logarithmic phase and arabitol in the stationary phase. A saprophytic hyphomycete, *Cladosporium glycolicum*, was found growing on submerged wood panels at a salinity exceeding 4.5 mol/L NaCl in the Great Salt Lake. Halophilic fungi, e.g. *Polypaecilum pisce* and *Basipetospora halophila*, have also been isolated from salted fish (DasSarma and Arora 2001).

2.3 Vesicular Arbuscular Mycorrhiza (VAM)

Vesicular arbuscular mycorrhizal fungi commonly called as VAM occur naturally in saline environment (Khan and Belik 1994). Several researchers investigated the relationship between soil salinity and occurrence of mycorrhizae on halophytes. They reported that the number of VAM spores or infectivity of VAM fungi changed with change in salt concentration (Juniper and Abbott 1993). The stresses due to saline soils effect the growth of plants, fungus or both.

VA mycorrhizal fungi most commonly observed in saline soils are *Glomus* spp. (Juniper and Abbott 1993), and this suggests that this may be adapted to grow in saline conditions, but ecological specificity has not been demonstrated. There is evidence that VAM species distribution is markedly changed with increased salinity (Stahl and Williams 1986). Aliasgharzadeh et al. (2001) observed that the most predominant species of Arbuscular mycorrhizal fungi (AMF) in the severely saline soils of the Tabriz plains were *Glomus intraradices*, *G. versiform* and *G. etunicatum*. The authors also found that the number of AMF spores did not significantly decrease with soil salinity and reported a relatively high spore number (mean of 100 per 10 g soil). The higher fungal spore density in saline soils may be due to the fact that sporulation is stimulated under salt stress which means that AMF may produce spores at low root-colonization levels in severe saline conditions (Aliasgharzadeh et al. 2001). Landwehr et al. (2002) reported abundant occurrence of AMF spores in extremely alkaline soils of pH values up to 11, independently of the soil type and irrespective of NaCl, Na_2CO_3, Na $_2SO_4$ or $CaSO_4$ salt types, though the degree of colonization varied from one individual to the next.

In most of the earlier studies, the identification of the AMF spores was based mainly on the morphological criteria. Complementary to morphology-based identification methods, use of molecular techniques such as polymerase chain reaction and restriction fragment length polymorphism for identification of AMF has been on the rise. There are few studies indicating that mycorrhizal fungi can increase growth of plants growing in saline habitats (Ojala et al. 1983; Pond et al. 1984). VA mycorrhizal fungi may have the ability to protect plants from salt stress, but the mechanism is not fully understood. The few data available at present suggest that fungi do have a potential to enhance plant growth by increasing the uptake of the nutrients. The efficacy of three species of AMF—*Glomus mosseae*, *G. intraradices* and *G. claroideum*—were tested to alleviate salt stress in olive trees under nursery conditions (Porras-Soriano et al. 2009). The authors observed that *G. mosseae* was the most efficient fungus in terms of olive tree performance and particularly in the protection offered against the detrimental effects of salinity. These findings suggest that the capability of AMF in protecting plants from the detrimental effects of salt stress may depend on the behaviour of each species.

3 Mechanisms for Halotolerance

Halotolerance is the adaptation of living organisms to conditions of high salinity. High osmolarity in hypersaline conditions can be deleterious to cells, since water is lost to the external medium until osmotic equilibrium is achieved. Many microorganisms respond to increase in osmolarity by accumulating osmotica in their cytosol, which protects them from cytoplasmic dehydration (Yancey et al. 1982). As biological membranes are permeable to water, all microorganisms have to keep their cytoplasm at least isosmotic with their environment to prevent water loss of cellular water; when a turgor pressure is to be maintained, the cytoplasm should even be slightly hyperosmotic. Adaptation to conditions of high salinity has an evolutionary significance. The concentration of brines during prebiotic evolution suggests haloadaptation at earliest evolutionary times (Dundas 1998). Osmophily is related to the osmotic aspects of life at high salt concentrations, especially turgor pressure, cellular dehydration and desiccation. Halophily refers to the ionic requirements for life at high salt concentrations.

Halophilic microorganisms usually adopt either of the two strategies of survival in saline environments: 'compatible solute' strategy or 'salt-in' strategy (Ventosa et al. 1998). When an isosmotic balance with the medium is achieved, cell volume is maintained. Compatible solute strategy is employed by the majority of moderately halophilic and halotolerant bacteria, some yeasts, algae and fungi. In this strategy cells maintain low concentrations of salt in their cytoplasm by balancing osmotic potential through the synthesis or uptake of organic compatible solutes and exclusion of salts from cytoplasm as much as possible. The compatible solutes or osmolytes, small organic molecules that are soluble in water to molar concentrations, which accumulate in halophiles are available in great spectrum and used in all three domains of life. These are assigned in two classes of chemicals, i.e. (1) the amino acids and their derivatives, such as glycine betaine, glutamine, glutamate, proline, ectoine or N-acetyl-β-lysine, and (2) polyols, e.g. glycine betaine, ectoine, sucrose, trehalose and glycerol, which do not disrupt metabolic processes and have no net charge at physiological pH. The accumulation can be accomplished either by uptake from the medium or by de novo synthesis (Shivanand and Mugeraya 2011).

The salt-in strategy is employed by true halophiles, including halophilic *Archaea* and extremely halophilic bacteria. Because of these the microorganisms that are adapted to high salt concentrations and cannot survive when the salinity of the medium is lowered (Arora et al. 2014a, b). They generally do not synthesize organic solutes to maintain the osmotic equilibrium. In this adaptation, the intracellular K^+ concentration is generally higher than that of outside, the intracellular Na^+ concentration is generally lower than that in the medium and the intracellular K^+ concentration increases with increasing external NaCl concentration in a non-linear pattern. All halophilic microorganisms contain potent transport mechanisms, generally based on Na^+/H^+ antiporters (Oren 1999).

Halobacillus is the first chloride-dependent bacterium reported, and several cellular functions depend on Cl^- for maximal activities, the most important being the activation of solute accumulation. *Halobacillus* switches its osmolyte strategy with the salinity in its environment by the production of different compatible solutes. Glutamate and glutamine dominate at intermediate salinities, and proline and ectoine dominate at high salinities. Chloride stimulates expression of the glutamine synthetase and activates the enzyme. The product glutamate then turns on the biosynthesis of proline by inducing the expression of the proline biosynthetic genes. *Halobacillus dabanensis* is used as a model organism to study the genes involved in halotolerance, including genes encoding Na^+/H^+ antiporters, enzymes involved in osmotic solute metabolism and stress proteins.

4 Applications of Halophilic Bacteria

Halophilic bacteria provide a high potential for biotechnological applications for at least two reasons: (1) their activities in natural environments with regard to their participation in biogeochemical processes of C, N, S, and P, the formation and dissolution of carbonates, the immobilization of phosphate, and the production of growth factors and nutrients (Rodriguez-Valera, 1993), and (2) their nutritional requirements are simple. The majority can use a large range of compounds as their sole carbon and energy source. Most of them can grow at high salt concentrations, minimizing the risk of contamination. Moreover, several genetic tools developed for the nonhalophilic bacteria can be applied to the halophiles, and hence their genetic manipulation seems feasible (Ventosa et al. 1998).

Halophilic bacteria have the ability to produce compatible solutes, which are useful for the biotechnological production of these osmolytes. Some compatible solutes, especially glycine, betaines and ectoines, may be used as stress protectants (against high salinity, thermal denaturation, desiccation and freezing) and stabilizers of enzymes, nucleic acids, membranes and whole cells. The industrial applications of these compounds in enzyme technology are most promising. The other compatible solutes such as trehalose, glycerol, proline, ectoines, sugars and hydroxyectoine from halophilic bacteria showed the highest efficiency of protection of lactate dehydrogenase against freeze-thaw treatment and heat stress.

Also, halophilic bacteria produce a number of extra- and intracellular enzymes and antimicrobial compounds that are currently of commercial interest (Kamekura and Seno 1990). Halophilic bacteria can produce enzymes that have optimal activity at high salinity, which is advantageous for harsh industrial processes.

The application of halophilic bacteria in environmental biotechnology is possible for (1) the recovery of saline soil, (2) the decontamination of saline or alkaline industrial wastewater and (3) the degradation of toxic compounds in hypersaline environments.

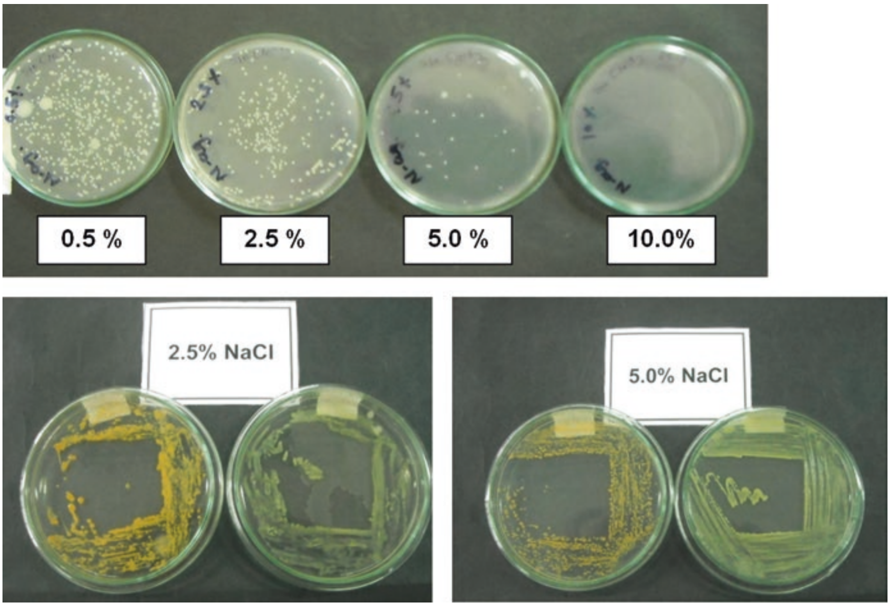
The use of halophilic bacteria in the recovery of saline soils is covered by the following hypotheses (Arora et al. 2014a, b). The first hypothesis is that microbial activities in saline soil may favour the growth of plants resistant to soil salinity. The second hypothesis is based on the utilization of these bacteria as bio-indicators in saline wells. Indicator microorganisms can be selected by their abilities to grow at different salt concentrations. These organisms could indicate that well water could be used with producing low saline contamination of plants or soils which could be alleviated by the desertification of soil. The last hypothesis is the application of halophilic bacterium genes using a genetic manipulation technique to assist wild-type plants to adapt to grow in saline soil by giving them the genes for crucial enzymes that are taken from halophiles.

4.1 Isolation of Halophilic Microbes from Rhizospheric Soils of Halophytes and Endophytes from Leaves

The rhizospheric soil samples from halophyte plant species were collected in duplicate from coastal Gujarat, India. The area is affected by soil salinity due to sea water ingress. The soil pH of the rhizospheric soil varied from 7.3 to 8.8 and salinity (electrical conductivity) varied from 2.7 to 39.6 dS m^{-1}.

Isolation of microbes was carried on nutrient agar medium and studied for colony and morphological characteristics in relation to soil biochemical properties. Salt tolerance of isolates was also determined varying NaCl concentrations of 0.5–20 %. It was found that 7 out of 44 isolates of various rhizospheric soil samples were able to tolerate salt concentration up to 10 %, while 29 isolates were able to tolerate salt concentration up to 5 % NaCl. Thus, from the rhizosphere of various halophytes and other salt tolerant plant species, various halotolerant bacteria, which were able to tolerate salt concentrations up to 10 % NaCl, have been isolated.

Growth of bacteria on nutrient media with different NaCl concentration



Out of 13 isolates that were able to tolerate salt concentration up to 15 % NaCl, 3 were from the rhizospheric soil of *Capparis decidua*, 2 each from both rhizospheric soil of plants of *Capparis decidua* and *Salvadora oleoides* and 1 each from the rhizospheric soil of *Cressa cretica*, *Aeluropus lagopoides* and *Suaeda maritima*.

4.2 Isolation of Halophilic Endophytic Bacteria

Nutrient agar plates inoculated with leaf extracts of four dominant halophytes or salt-tolerant plants from coastal Gujarat showed morphologically different bacterial colonies. Twenty isolates were selected for further investigations based on their fast growth. The bacterial counts were found maximum in *Sphaeranthus indicus* (40 %) and were minimum in *Salicornia brachiata* (10 %).

Of the 20 endophyte isolates selected, 3 were pigmented and 17 were nonpigmented isolates. Regarding cell shape and Gram's staining, seven were Gram-negative cocci, two Gram-positive cocci, four Gram-negative bacilli and seven Gram-positive bacilli. Motility test results depicted that 18 isolates were motile, while only 2 isolates were nonmotile. In total, 11 isolates showed positive results for oxidase test, whereas all endophytic bacterial cultures showed negative catalase test. The enzymatic activity of endophytic isolates revealed that 50 % isolates exhibited amylase activity, and only 15 % isolates showed urease activity (Arora et al. 2014a).

Of 20 endophytic bacterial isolates screened for plant growth-promoting substances, 6 (30 %) and 2 (10 %) isolates showed positive results for ammonia production and phosphate solubilization activity. Only 4 (20 %) were mixed acid fermenters, 5(25 %) showed the production of acetoin and none of the isolates exhibited IAA production (Arora et al. 2014a). The selected bacterial isolates were submitted for 16S rRNA gene sequencing, and it was observed that *Acinetobacter baumannii*, *Bacillus cereus*, *Bacillus firmus*, *Bacillus aerius*, *Pseudomonas fluorescens* and *Bacillus subtilis* were positive for ammonia production, while phosphate solubilization was positive for *Acinetobacter baumannii* and *Pseudomonas fluorescens*.

4.3 Tolerance to Sodium Chloride

All the 20 endophytic bacteria showed good growth at 2.5 % NaCl concentration while 18 (90 %) isolates grow up to 5 % NaCl, 17 (85 %) isolates showed growth at 7.5 % NaCl and 15 (75 %) tolerated up to 10 % NaCl concentration. *Bacillus foraminis* and *Bacillus gibsonii* could tolerate up to 7.5 % NaCl, while *Acinetobacter baumannii* and *Paenibacillus xylanisolvens* tolerated only up to 2.5 % NaCl concentration and *Pseudomonas fluorescens* up to 5 % NaCl. All the other isolates were able to tolerate 10 % NaCl concentration in media. Overall, the growth rate of endophytes decreased with increasing concentration of NaCl in the media.

5 Bioremediation Potential of Halophilic Bacteria

There is high potential for bioremediation of salt-affected soils using applications of halophilic bacteria. The applications of halophilic bacteria include recovery of saline soil by directly supporting the growth and stress tolerance of vegetation, thus indirectly increasing crop yields in saline soil. The biotic approach ‘plant-microbe interaction’ to overcome salinity problems has recently received considerable attention throughout the world. Plant-microbe interactions are beneficial associations between plants and microorganisms and also a more efficient method for reclamation of saline soils. Bacteria are more commonly in this technique than fungi.

Two promising halophilic bacterial strains that showed positive for plant growth promotion were selected and tested for salt removal efficiency. Halophilic bacteria strain (CSSRO2) was more efficient in reducing sodium concentration from 112,230 ppm in supernatant to 100,190 ppm at 24 h while strain CSSRY1 reduced Na concentration to 92,730 ppm at 48 h in halophilic broth with 15 % NaCl. This shows that inoculation of strains in liquid media resulted in removal of 12,040 and 19,500 ppm of Na by halophilic bacterial strains CSSRO2 and CSSRY1, respectively. The halophilic bacteria strains CSSRY1 and CSSRO2 were also shown to have high potential for removal of sodium ions from soil. CSSRY1 efficiently removed sodium at higher (6, 8, 10 % NaCl) salt concentration in comparison of CSSRO2 and association of both organisms (CSSRY1 and CSSRO2). This was also confirmed by reduction of electrical conductivity or total dissolved salts (TDS). It is hypothesized that once the sodium ion concentration is reduced in rhizosphere, plants are able to resume nutrient and water uptake.

To confirm about the sodium removal efficacy of these halophilic bacterial strains from soil, CSSRY1 and CSSRO2 were inoculated in sterile soil to test their efficacy for sodium removal from the soil containing different concentrations of NaCl (0–10 % NaCl). It was observed that inoculation of strain CSSRY1 decreased soluble sodium content up to 31 % at 4 % NaCl concentration while at 10 % NaCl concentration, it reduced only 19 % sodium from soil.

These selected cultures were further studied in greenhouse pot experiments for plant growth promotion. Results showed there was increase in plant growth parameters and yield of wheat when halophilic bacteria were inoculated with seeds, and saline water irrigation was applied. It was observed that there was 10–12 % increase in yield attributes and yield of wheat at 6 % NaCl as compared to 2 % NaCl. In the 5 % NaCl treated soil, only the growth of the *Zea mays* was observed. Plants inoculated with a consortium of halophilic bacteria also showed growth at 10 % NaCl, whereas inoculation with single isolates did not promote plant growth at this salt concentration. The maximum fresh weight, dry weight, shoot length and root length of plant were found in the case of ‘consortium 5 % NaCl’-treated pot, 194.5 % increase in fresh weight, 98.97 % increase in dry weight, 15.37 cm increase in shoot length and 7.4 cm increase in root length as compared to the uninoculated control plants. The results show that inoculation with these bacterial isolates can promote the growth of plants in salt-affected soils due to production of hormone auxin and

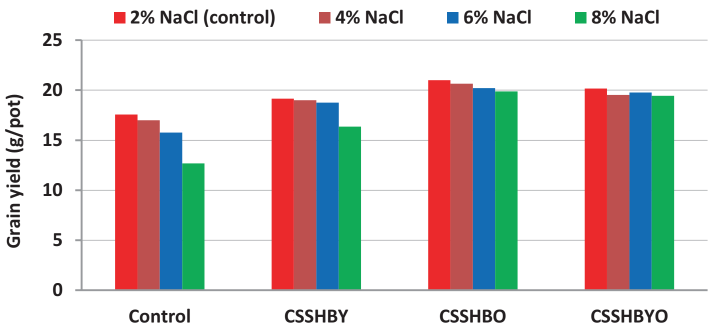


Fig. 1 Wheat performance with halophilic bacteria inoculation under different salinity

Table 2 Plant growth promotion of halophilic bacteria on inoculation with maize

Halophilic culture	Treatment (conc. of NaCl)	Fresh weight (g/pot)	Dry weight (g/pot)	Shoot length (cm)	Root length (cm)
MB55	5 %	1.945	0.660	14.50	12.00
MB66	5 %	2.920	0.505	25.00	16.80
MB90	5 %	2.900	0.665	18.36	17.16
MB94	5 %	2.825	0.855	11.15	13.80
Consortium	5 %	5.595	0.975	27.07	17.80
Consortium	10 %	2.075	0.700	8.90	11.26
Control	5 %	1.900	0.490	11.7	10.40

thus enhanced root growth. Another very likely mechanism may be alleviation of salinity stress via plant growth-promoting rhizobacteria that express ACC deaminase activity. This enzyme removes stress ethylene from the rhizosphere. Also, the halophilic/halotolerant bacteria remove sodium from the surrounding soil and thus useful in plant growth promotion in salt-affected soils (Fig. 1 and Table 2).

Halophilic microbes were found to have the ability to remediate the saline soil and can be used by glycophytes/crop plants for optimum growth under saline condition.

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Plant Growth-Promoting Bacteria: An Emerging Tool for Sustainable Crop Production Under Salt Stress

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1 Introduction

Climate change with an increasing world population is predicted to drastically increase the global requirement for cultivable farmland, which is a non-renewable or sparingly renewable resource and, hitherto, high in demand. With the world population expected to reach 10 billion by 2050, it is estimated that the global food supply will need to increase by 70 % to meet the rapidly rising demand (Ladeiro 2012). Changes in global climate may further compound this challenge, as predicted increases in the environmental stresses are expected to reduce the crop productivity. This might soon move towards loss of productive potential, loss of biodiversity, unsustainability and instability of soils, causing an insufficiency to feed the world's population. Feeding the gigantic population is thus an important challenge to meet, and it is essential to continuously increase and sustain the agricultural productivity in the coming decades (Glick 2014). The current agricultural productivity however is constrained by several environmental biotic and abiotic stresses that have caused major reductions in cultivable land area, crop quality and productivity. Among the abiotic stresses, soil salinization, acidification, drought, soil pH and environmental temperatures are the major limiting factors in sustainable crop production. Saline soils are a major issue for agriculture because salt turns agronomically useful lands into unproductive areas (Fig. 1). Thus salinization has been recognized as one of the most devastating soil degradation threats on the earth. It is an endangering potential use of soil on almost an estimated land area of

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Fig. 1 A patch of salt-affected soil

Table 1 Global distribution of salt-affected soils (Mha)

Regions	Total area (Mha)	Saline soils		Sodic soils	
		Mha	%	Mha	%
Africa	1899	39	2.0	34	1.8
Asia, the Pacific and Australia	3107	195	6.3	249	8.0
Europe	2011	7	0.3	73	3.6
Latin America	2039	61	3.0	51	2.5
Near East	1802	92	5.1	14	0.8
North America	1924	5	0.2	15	0.8
Total	12,781	397	3.1 %	434	3.4 %

Source: FAO. Land and plant nutrition management service (2008)

1 billion ha globally, representing about 7 % of earths continental extent, with about 1–3 million ha land area in Europe, about 850 million ha in Asia, 104 million ha in Pacific subregion (Rengasamy 2006; Ladeiro 2012) and about 7 million ha in India (Patel and Dave 2011). It has also been estimated that worldwide, about 20 % of total cultivated land areas are affected by high salinity and the salinized areas are increasing at the rate of 10 % annually due to reasons like low precipitation, high surface evaporation, weathering of native rocks, irrigation with saline water and poor cultural practices, hitting hardest in the arid and semiarid regions (Table 1). Furthermore, it is anticipated that about more than 50 % of the arable lands would turn salinized by 2050 (Jamil et al. 2011).

The agricultural crops under salinity exhibit a spectrum of responses ranging from crop yield declines through alterations in soil physico-chemical properties to disturbance in the ecological balance of the region. It is a major cause of land abandonment and aquifers for agricultural purposes and a major factor for reducing crop productivity. The impacts include poor agricultural productivity, low economic returns and soil erosions (Hu and Schmidhalter 2002). The poor crop productivities are resultant of complex interactions among morphological, physiological and biochemical processes through salinity-induced limited water and nutrient uptakes throughout the crop growth cycle (Akbarimoghaddam et al. 2011; Singh and Chatrath 2001). Limited water and nutrient uptakes affect almost every developmental stage of the crop with osmotic and oxidative stress, nutrient (N, Ca, K, P, Fe and Zn) deficiency and ion toxicity (Munns 2002). Ion toxicity through excessive accumulation of salt ions in cell walls leads to osmotic stress, causing replacement of K^+ by Na^+ in biochemical reactions and inducing conformational changes in proteins. Similarly, enzyme activities during the developmental stages get affected as K^+ ions, which act as cofactors and are required for binding tRNA to ribosomes. Substitution of K^+ by Na^+ also affects the protein synthesis adversely (Zhu 2002). Metabolic imbalance, caused by ion toxicity and osmotic stress, in turn, leads to oxidative stress (Chinnusamy et al. 2006), resulting in failure in osmotic balance, loss of cell turgidity and cell dehydration, ultimately culminating in cell death. As several salts are also plant nutrients, high salt levels in the soils upset the nutrient balance in the plant or interfere with the uptake of few other important nutrients (Blaylock 1994). For example, plant phosphorus (P) uptake gets significantly reduced because phosphate ions precipitate with Ca ions (Bano and Fatima 2009). Limited water uptake and nutrient imbalance begin to affect photosynthetic processes through decrease in photosystem II efficiency, reduction in leaf area, chlorophyll content and stomatal conductance during the crop cycle (Netondo et al. 2004). Later, prior to harvest stage, soil salinization also imposes microsporogenesis and stamen filament elongation, enhancing programmed cell death in some tissue types, ovule abortion and senescence of fertilized embryos, affecting the reproductive development adversely. Recent reports also show that salinity adversely affects DNA, RNA, protein synthesis and mitosis in crops (Tabur and Demir 2010; Javid et al. 2011). Overall, salinity decreases yields of many crops as it inhibits plant photosynthesis, protein synthesis and lipid metabolism and physiological (Munns and James 2003) and molecular development at every stage of growth (Tester and Davenport 2003; Fisher et al. 2012).

The historical approach to mitigate the negative effects of salinity on crop yield has been the creation of salinity-tolerant cultivars. Conventional breeding techniques have enabled the development of crop varieties with increased yields and greater tolerance to salinity, but both are time and labour intensive. Genetic engineering of crops with improved stress tolerance is faster but comes with its own set of drawbacks. Furthermore, both methods often neglect the complex ecological context of the soil environment in which the crop is grown. Among the visible solutions till date that can produce more agricultural yield are (1) effective agricultural land, water and nutrient management, (2) appreciable and guarded use of efficient pesticides and herbicides, and (3) enhanced advocacy of transgenic crops. However, as the world we live in is finite with limited resources, enhancing the agricultural yields through the mentioned solutions cannot be sustained and will fetch only short-term success. Thus, though important insights on mechanisms of salt tolerance in plants have been gained, transfer of such knowledge into crop for improving productivity has been limited, and any technology for overcoming this constraint shall be ineluctable. Several commentators, therefore, have suggested that it would be felicitous to look for an effective and long-term solution through sustainable and eco-friendly biological solutions.

Plant growth-promoting bacteria have received considerable attention for their ability to confer several benefits to crop productivity and salinity resistance in the recent years. Glick (2014) quoted emphatically that 'Scientists have dramatically increased our knowledge of the mechanisms employed by PGPR in the past 15–20 years, additional understanding of the fundamental mechanisms employed by these bacteria will hasten the acceptance of these organisms as suitable and effective adjuncts to agricultural practices'. Scientific architects have hypothesized that the assiduous use of plant growth-promoting rhizobacteria (PGPR) in agriculture shall prove to be a long-term, striking and sustainable technology for overcoming the saline constraints (Flowers 2004; Munns and Tester 2008; Rodriguez and Redman 2008). The present chapter highlights the advantages associated with PGPR-based mechanics with a focus on increased tolerance to salinity and the conceptual understanding of crop productivity under stress as a complex product of plant genetics and microbial community function. We also accentuate the direct and indirect mechanics of PGPR through (a) bio-fertilization, (b) stimulation of root growth, (c) rhizo-remediation and (d) plant antibiosis and induction of systemic resistance, nutrient competition and niches that assist to sustain healthy growth of plants enhancing the crop productivity.

2 Soil Salinity: The Technical Issues

2.1 Soil Salinization Process

Land is a limiting resource, considering the fact that there are only about 5 million km^2 available for future sustainable land use. Although earth abounds in water, an almost negligible portion (~2.5 % or 35 million km^3) is fresh or with low salt concentration (<1 dS/m), i.e. water that may be conditionally used for irrigation in crop production, whereas the rest is salty and therefore unsuitable for irrigation (Ondrasek et al. 2010). It has been estimated that irrigated agriculture consumes ~70 % (and >90 % in many developing countries) of total water withdrawal to produce ~36 % of global food (Howell 2001). As a consequence, there is a continuous degradation of land resources (e.g. salt-affected soils), representing a large burden to natural ecosystems. According to FAO, Land and Plant Nutrition Management Service (2008), over 6 % of the world's land is affected by either salinity or sodicity. The major causes of naturally induced salinity are salt water intrusion and wind-borne salt deposition in land. Another major cause for soil salinity is the deposition of oceanic salt carried in wind and rain. Salts also originate from mineral weathering. The anthropogenic factors include crop irrigation with salt waters through which soil salinization gets dramatically exacerbated and accelerated. The other factors include inorganic fertilizers and soil amendments through gypsum, composts manures, etc.

Salinization is a natural or human-induced process that results in accumulation of dissolved salts in soil water to an extent that inhibits plant growth. The processes may be primary (natural) and secondary (anthropogenic) in nature. It involves accumulation of water-soluble salts in soil that includes potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and sodium (Na^+) ions. Depending on soils, the extracted solutions differ in content of dissolved salts. The salt concentration, with electrical conductivity (ECse), exceeds 20 mM (~2 dSm^{-1}) and is categorized as salt affected (Abrol et al. 1988). A saline soil thus is defined as soil having a high concentration of soluble salts (EC_e of 4 dSm^{-1} or more) that are enough to affect plant growth. However, many crops are affected by soil with an EC_e less than 4 dSm^{-1}. Excessive sodium (Na^+) accumulation from salt destroys soil structure, deteriorates soil hydraulic properties, raises soil pH and reduces water infiltration and soil aeration, leading to soil compaction, increasing erosion and water run-off. Furthermore, sodium, being the most pronounced destructor of secondary clay minerals by dispersion, replaces calcium (Ca^{2+}) and other coagulators like Mg^{2+} and gets adsorbed on the surface and/or interlayers of soil aggregates (Ondrasek et al. 2010). Dispersed clay particles undergo leaching through the soil to accumulate and block pores, especially in fine-textured soil horizons. The soil becomes unsuitable for proper root growth and plant development. The secondary result are salinity-induced sodicity, where leaching either through natural or human-induced processes washes away the soluble salts into the subsoil and leaves negative charges of sodium bound to the clay.

2.2 *Salinity Impacts on Rhizosphere-Associated Microbes*

Bacteria are adsorbed onto soil particles by ion exchange, and a soil is considered to be naturally fertile when the soil organisms are releasing inorganic nutrients from the organic reserves at a rate sufficient to sustain rapid plant growth. Since the soil organic matter and consequently the biomass and microbial activity are generally more relevant in the first few centimetres at the surface of the soil, salinization close to the surface significantly affects a series of microbiologically mediated processes. Along with it disturbs the natural ecosystem functioning and plant health. For rhizobacteria, life in high salt concentrations is bioenergetically taxing because they must maintain an osmotic balance between their cytoplasm and the surrounding medium while excluding sodium ions from the cell interior, and as a result, sufficient energy is required for adaptation. Depletion of potassium ions by plants under saline conditions further reduces the ability of rhizobacteria to use potassium ions as a primary osmoregulator. Plant use of osmolytes under salt stress deprives rhizobacteria of osmolytes, which finally limits the bacterial growth. The salinity level above 5 % thus reduces the total count of bacteria and actinobacteria drastically. In addition, it inhibits nitrogen fixation, root exudation and decomposition of organic matter. Significant negative correlations between soil electrical conductivity and total CO_2 emission or microbial biomass C have also suggested that it has severe adverse effect on microbial biomass and activities. Naturally occurring soil organic matter decomposers thus become sensitive to salt-induced stress, and the effect is always more pronounced in the rhizosphere pursuant to increased water uptake by the plants due to transpiration. Alteration of proteins, exo-polysaccharide and lipopolysaccharide composition of the bacterial cell surface, impairment of molecular signal exchange between bacteria and their plant host due to the alteration of membrane glucan contents and inhibition of bacterial mobility and chemotaxis towards plant roots significantly affect microbial diversity in the rhizosphere, under saline conditions. Overall, salinity has a negative impact on microbial abundance, diversity, composition and functions.

2.3 Soil Salinity Effects on Plant Growth and Development

During the onset and development of salt stress within a plant, all the major processes such as germination, cell division and elongation, leaf growth, leaf expansion, photosynthesis, protein synthesis and energy and lipid metabolism are adversely affected (Fig. 2). During the vegetative stages, salt stress induces stomatal closure, leading to reduction in CO_2 assimilation and transpiration. The reduced turgor potentials affect the leaf expansion and leaf area, which in turn reduces the light

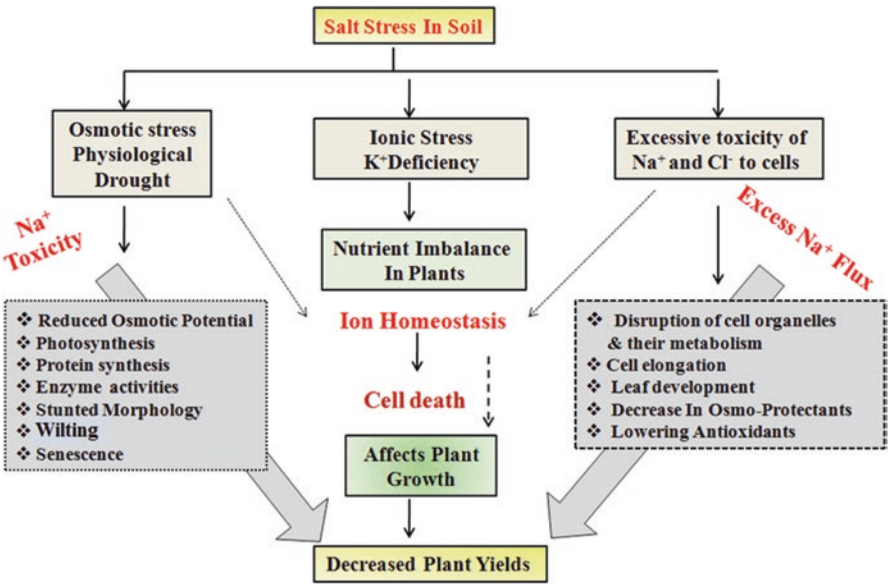

Fig. 2 Effect of salt stress on crop growth and development

interception and photosynthetic rates, coupled with spurt in respiration resulting into reduced biomass accumulation. Excessive salts reduce the water potential of soil, making the soil solution unavailable to the plants and creates physiological drought. Also, osmotic pressure in the rhizosphere solution exceeds in root cells which reduces water and nutrient uptake. Salinity further creates nutritional imbalance through increase in uptake of Na^+ or decrease in uptake of Ca^{2+} and K^+ in leaves. Excess Na^+ causes metabolic disturbances in processes where low Na^+ and high K^+ or Ca^{2+} are required for optimum growth and developmental functions. Excess sodium and more importantly chlorides affect plant enzymes and cause cell swelling, resulting in reduced energy production and other physiological changes. Uptake and accumulation of Cl^- disrupts the photosynthetic function through inhibition of nitrate reductase activity. Under excessive Na^+ and Cl^- rhizosphere concentrations, competitive interactions with other nutrient ions (K^+, NO_3^- and $H_2PO_4^-$) occur for binding sites and transport proteins in root cells that have adverse effects on translocation, deposition and partitioning within the plant. Once the capacity of cells to store salts is exhausted, salt build-up in intercellular space leads to cell dehydration and death. Plants suffer from membrane destabilization and a general nutrient imbalance. All micro- and macronutrient contents decrease in roots and shoots with increasing NaCl concentration in the soil. Osmotic stress decreases cell growth and development, reduces leaf area and chlorophyll content, accelerates defoliation and senescence and reduces the yields. The primary salinity effects give rise to numerous secondary ones such as oxidative stress, characterized by accumulation of reactive oxygen species potentially harmful to bio-membranes, proteins, nucleic acids and enzymes. The plants with perturbed nutrient relations are more susceptible to invasion of different pathogenic microorganisms and physiological dysfunctions, whereas their edible parts have markedly less economic and nutritional value due to reduced fruit size and shelf life, non-uniform fruit shape and decreased vitamin contents.

3 Mitigating Salinity Stress Through Plant Growth-Promoting Rhizobacteria: Emerging Roles

3.1 Plant Growth-Promoting Rhizobacteria (PGPR)

Microbial populations are present in diverse ecological niches, in both lithosphere and hydrosphere, where their metabolic abilities play a critical role in geochemical nutrient cycling. Rhizosphere is a well-characterized ecological niche comprising of soil volume surrounding the plant roots with highest microbial population as defined by Hiltner (1904). The bacterial population in the rhizosphere is 100–1000 times higher than in bulk soil. Bacterial flora, dispersed within the soil, is often attached to soil particles and interacts with the roots of plants. It has the ability to grow rapidly and utilize a very wide range of different substances as nutrient sources due to its metabolic versatility to adapt and utilize root exudates efficiently. Along with this, about 15 % of plant root surface is covered by microbial populations belonging to several bacterial species, and metabolic activities of these bacteria kindle mineral nutrient transport and uptake by the plant roots (Glick 1995, 2014).

A putative rhizobacterium qualifies as plant growth-promoting rhizobacteria (PGPR), once it enables induction of a positive effect on the plant and demonstrates good competitive skills over the existing rhizosphere communities. Such a bacterium is characterized by the three inherent distinctivenesses: (1) it should possess proficiency to colonize the root surface; (2) it should be able to survive, multiply and compete with other micro biota, at least till the time it expresses its plant growth promotion and protection activities; and (3) it should aid to augment the plant growth. PGPRs have also been classified on basis of their functional activities as (1) bio-fertilizers (to increase plant nutrient availability), (2) phytostimulators (plant growth promotion, through phytohormones), (3) rhizo-remediators (degrading organic pollutants) and (4) biopesticides (control diseases through production of antibiotics and antifungal metabolites) (Antoun and Prévost 2005). Several other definitions state that when reintroduced by plant inoculation in a soil containing competitive microflora, if about 2–5 % of rhizobacteria exert a beneficial effect on plant growth, they can be coined as plant growth-promoting rhizobacteria (Kloepper and Schroth 1978). In accordance, soil bacterial species burgeoning in plant rhizosphere which grow in, on or around plant tissues stimulate plant growth by a plethora of mechanisms and are known as plant growth-promoting rhizobacteria (Vessey 2003).

A single PGPR during its proximity to the root and intimate association functions through multiple modes of action including biological control (Vessey 2003). It is classified into extracellular (ePGPR), which exists on the rhizoplane, or in the spaces between cells of the root cortex, and intracellular (iPGPR), which exists inside root cells, generally in specialized nodular structures. Some examples of ePGPR are *Agrobacterium*, *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Burkholderia*, *Caulobacter*, *Chromobacterium*, *Erwinia*, *Flavobacterium*, *Micrococcous*, *Pseudomonas*, *Serratia*, etc. While few examples of iPGPR are *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, *Mesorhizobium and Rhizobium* of the family *Rhizobiaceae*. *Micromonospora*, *Streptomyces* spp., *Streptosporangium* and *Thermobifida* are among few of them which have shown an enormous potential as biocontrol agents against different root fungal pathogens and are worthy of mention. The role of PGPR is not solely implemented by the direct effect of a single bacterial strain but also by the molecular dialogue established among soil microorganisms and plants. PGPRs thus are the potential tools for sustainable agriculture.

3.2 Direct and Indirect Plant Growth-Promoting Rhizobacteria (PGPR) Mechanics

Plant growth-promoting (PGP) mechanics involves processes through which rhizospheric flora maximizes the processes that strongly enrich plant productivity. Traditionally, PGP mechanisms have been grouped into direct and indirect mechanisms. Indirect mechanisms occur outside the plant, while direct mechanisms happen inside the plant and directly affect the plant's metabolism (Antoun and Prévost 2005; Siddikee et al. 2010). Consequently, direct mechanisms affect the balance of plant growth regulators, either because the microorganisms themselves release growth regulators that are integrated into the plant or because the microorganisms themselves act as a sink of plant-released hormones and those then induce an improvement in plant metabolism via its adaptive capacity (Glick 2014; Govindasamy et al. 2011). Indirect mechanism requires the participation of the plant's defensive metabolic processes, which respond to the signal sent from the bacteria influencing the plant. Two important mechanisms included in this group are protection against abiotic stress and induction of systemic resistance to plant pathogens (Aeron et al. 2011; Glick 2014; Jha et al. 2011; Ramos-Solano et al. 2008).

3.2.1 Direct Mechanics of Plant Growth-Promoting Rhizobacteria

Rhizobacterial Biological Nitrogen Fixation (as Bio-fertilizers)

Rhizobacterial nitrogen fixers have been categorized on basis of their specificities to the plants. Root-/legume-associated symbiotic bacteria possess the specificity and infect the roots to produce nodule, e.g. *Rhizobium* strains (Fig. 3), while the free-living nitrogen fixers, namely, *Azospirillum*, *Azotobacter*, *Burkholderia*, *Herbaspirillum*, *Bacillus* and *Paenibacillus*, don't possess specificity to plant (Oberson et al. 2013). Although free-living nitrogen fixers do not penetrate the plant's tissues, yet a very close relationship is established where these bacteria live sufficiently close to the root such that the atmospheric nitrogen fixed by the bacteria is not used for their own benefit but is taken up by the plant, allowing better availability of nitrogen

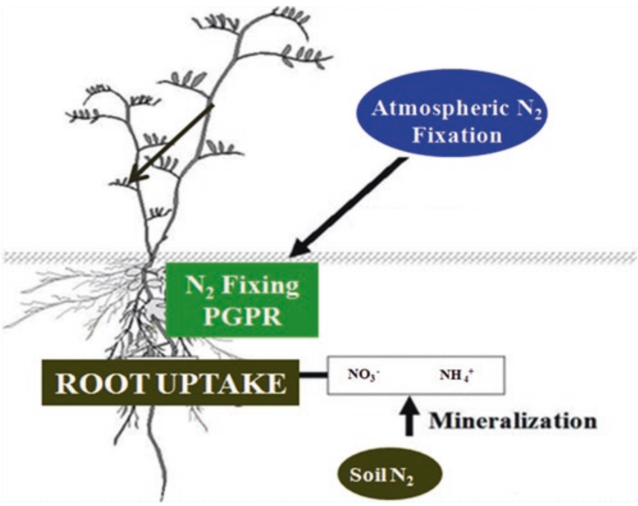

Fig. 3 Plant growth-promoting rhizobacterial biological nitrogen fixation

absorption through a non-specific and loose symbiosis. The amount of nitrogen fixed ranges between 20 and 30 kg per hectare per year (Stacey et al. 1992). Several genera have gained importance as along with nitrogen fixation, they also enhance plant growth by producing phytohormones including indole-3-acetic acid, gibberellic acid and cytokinins. Application of *Azotobacter chroococcum* and *Azospirillum brasilense* inoculants in agriculture, especially in cereals, has resulted in notable increases in crop yields (Oberson et al. 2013). *Bacillus* and *Paenibacillus* have gained importance over the period of time due to nitrogen fixation ability as they have been reported to possess *nif* gene cluster which is responsible to code nitrogenase enzyme, a key enzyme required for fixing nitrogen. Hence, nitrogen fixation is considered as an important trait of PGPRs as it directly provides nitrogen to the plant and is being marketed as bio-fertilizers for the past 20 years.

Rhizobacterial Phosphate Solubilization

After nitrogen, phosphorous is the most limiting nutrient for plants which despite profound abundance in soils remains unavailable in form suitable for plant uptake. Phosphate tends to react with calcium (Ca), iron (Fe) or aluminium (Al) leading to its precipitation, making it unavailable for plant uptake. It is estimated that phosphate-solubilizing microorganisms constitute 20–40 % of the culturable population of soil microorganisms, of which significant proportion of these bacteria can be isolated from rhizosphere soil. Plants are only able to absorb mono- and dibasic phosphates which are the soluble forms of phosphate (Jha et al. 2012; Jha and Saraf 2015). Rhizobacteria mineralizes organic phosphorus in soil by solubilizing complex-structured phosphates, viz. tricalcium phosphate, rock phosphate, aluminium phosphate, etc., which turns organic phosphorous to inorganic form ultimately aiding the phosphate availability to plants. A bacterium uses different mechanisms to solubilize the insoluble forms of the phosphate. But the primary mechanism is based on organic acid secretion by them because of sugar metabolism. Organisms residing in the rhizosphere utilize sugars from root exudates and metabolize it to produce organic acids (Goswami et al. 2014). These acids act as good chelators of divalent Ca^{2+} cations, accompanying the release of phosphates from insoluble phosphatic compounds (Fig. 4). Among the soil bacterial communities, ectorhizospheric (residing on roots and in rhizospheric soil) strains from *Pseudomonas* and *Bacilli* and endosymbiotic (residing within the roots/nodules) rhizobia have been described as most effective phosphate solubilizers (Goswami et al. 2014).

Rhizobacterial Phytohormone Production

Rhizobacteria possess the potential to produce well-known phytohormones like indole-3-acetic acid (IAA), gibberellins, cytokinins, ethylene and abscisic acid (Arshad and Frankenberger 1998; Patten and Glick 1996). Plant responds to any of these phytohormones that are supplemented externally or have been produced by

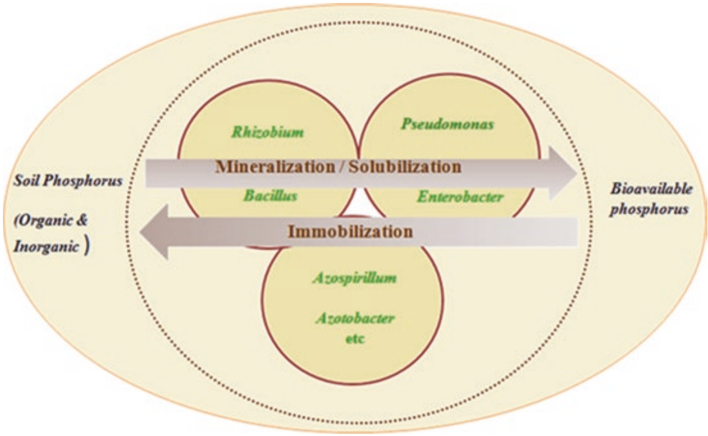

Fig. 4 Plant growth-promoting rhizobacterial soil phosphorus solubilization

microbial flora residing in the rhizosphere. These phytohormones can mediate processes including plant cell enlargement, division and extension in symbiotic as well as non-symbiotic roots (Glick 2014).

Rhizobacterial IAA Production

Auxins control several stages of plant growth and development such as cell elongation, cell division, tissue differentiation and aid apical dominance. Indole-3-acetic acid (IAA) is an important auxin produced by several strains of PGPR and increases the plant growth through increase in cell elongation, cell division and differentiation (Amara et al. 2015). About 80 % of the bacterial flora in the rhizosphere produces IAA. PGPRs residing in rhizosphere, rhizoplane and endophytic niches can produce IAA and support plant growth. Rhizobacteria enhance the endogenous IAA levels of plant and have remarkable effect on plant growth. Plant under the long-term treatment of IAA has highly developed roots, which in turn allows the plant to uptake better nutrients, ultimately aiding overall growth of the plant (Aeron et al. 2011). IAA released by rhizobacteria mainly affects the root system by increasing its size and weight, branching number and the surface area in contact with soil. All these changes lead to an increase in its ability to probe the soil for nutrient exchange, therefore improving plant's nutrition pool and growth capacity (Ramos-Solano et al. 2008). IAA also drives the differentiation of adventitious roots from stem as auxins induce stem tissues to redifferentiate as root tissue. Different PGPRs possess different routes for the synthesis of IAA. IAA is synthesized by plant-associated microbes via L-tryptophan-dependent and L-tryptophan-independent pathways, and three L-tryptophan-dependent pathways are known. Most of these PGPRs utilize L-tryptophan which is secreted in root exudates as a precursor for IAA production. Three

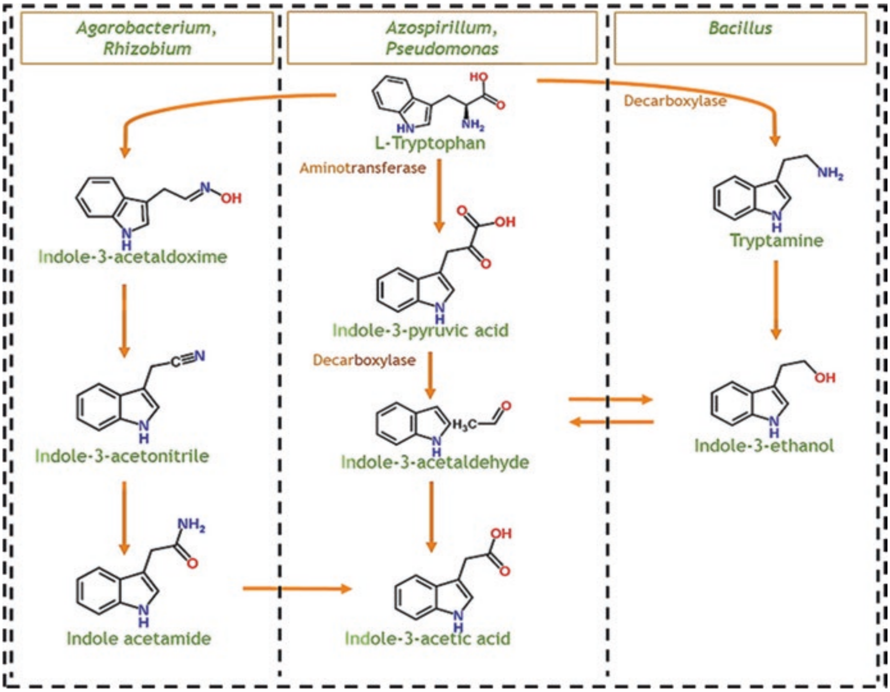

Fig. 5 Plant growth-promoting rhizobacterial tryptophan-dependent IAA production (Source: Goswami et al. 2016)

tryptophan-dependent routes for the production from L-tryptophan are described in Fig. 5. Concisely, *Rhizobium*, *Bradyrhizobium* and *Azospirillum* synthesize IAA via the indole-3-pyruvic acid (IPyA) pathway (Burdman et al. 2000), while *Agrobacterium tumefaciens*, *Pseudomonas syringae*, *Pantoea agglomerans*, *Rhizobium*, *Bradyrhizobium* and *Erwinia herbicola* synthesize IAA predominantly via indole-3-acetamide (IAM) pathway, whereas *Bacillus subtilis*, *B. licheniformis* and *B. megaterium* produce IAA via tryptamine pathway (Dobbelaere et al. 2003).

Rhizobacterial Cytokinin (N6-Substituted Amino-Purine) Production

Cytokinins produced by rhizobacteria enhance cell division, root development and root hair formation, inhibit root elongation and shoot initiation and improve several other physiological responses (Amara et al. 2015). Cytokinins too influence physiological and developmental processes such as the formation of embryo vasculature, nutritional signalling, leaf expansion, branching, chlorophyll production, root growth, promotion of seed germination and delay of plant senescence (Maheshwari et al. 2015). Cytokinin production in several plant-associated microbes has been well

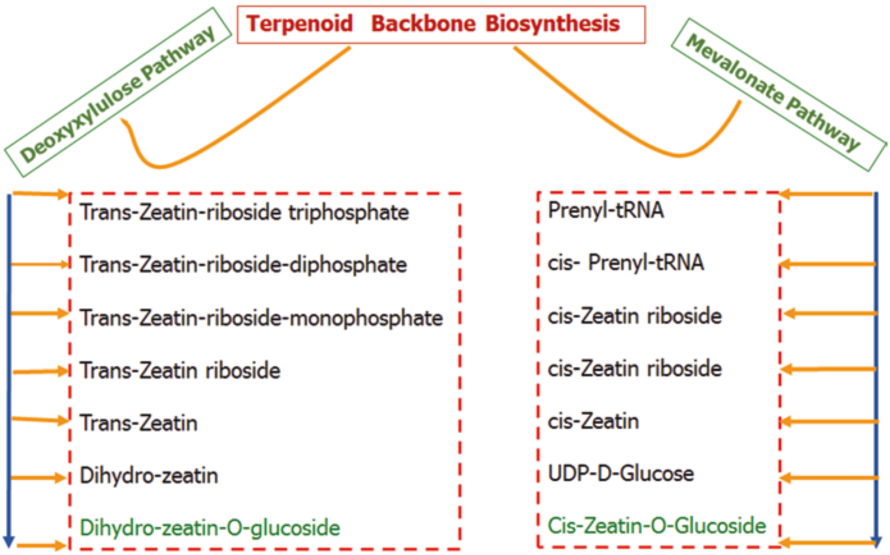

Fig. 6 Plant growth-promoting rhizobacterial cytokinin production (Source: Goswami et al. 2016)

characterized. Cytokinins are produced through two pathways: the direct pathway, which involves development of dimethylallyl diphosphate (DMAPP) and N6-isopentenyladenosine monophosphate (i6 AMP) from adenosine monophosphate (AMP), followed by formation of zeatin-type compounds from hydroxylation of the side chain, and indirect pathway, in which cytokinins are released by turnover of tRNA containing cis-zeatin (Amara et al. 2015). Zeatin, a cytokinin, widely produced by PGPR and their pathways of biosynthesis, is shown in Fig. 6. *B. megaterium* strain promoted the growth of *A. thaliana* and *P. vulgaris* seedlings through cytokinin production. Other different bacterial genera *Proteus*, *Klebsiella*, *Escherichia*, *Pseudomonas* and *Xanthomonas* have also been reported to possess the ability to produce cytokinins (Ortíz-Castro et al. 2008; Maheshwari et al. 2015).

Rhizobacterial Gibberellin Production

Gibberellins are a large group of phytohormones constituting as many as 136 different structured molecules with a skeleton of 19–20 carbon atoms. They influence several developmental processes in higher plants, including seed germination, stem elongation, flowering and fruit setting (Hedden and Phillips 2000). The reason for their pronounced effect is that these hormones get translocated from the roots to the aerial parts of the plant. The effects in the aerial part are notable, and more so, when they are produced by bacteria, they stimulate the root system and enhance the nutrient supply, facilitating growth in the aerial parts (Wong et al. 2015). To date, 136 GAs from 128 plant species are known and 28 GAs from 7 fungal species, and only

4 GAs (GA_1, GA_3, GA_4 and GA_{20}) from 7 bacterial species have been identified (MacMillan 2001). *B. pumilus* and *B. licheniformis* have been reported to produce gibberellins (Gutierrez-Manero et al. 2001). Atzorn et al. (1988) reported presence of GA_1, GA_4, GA_9 and GA_{20} in gnotobiotic cultures of *Rhizobium meliloti*.

3.2.2 Indirect Mechanics of Plant Growth-Promoting Rhizobacteria

Rhizobacterial Siderophore Production

Siderophore are low-molecular weight compounds (usually <1 kDa), containing functional groups, capable of binding iron in a reversible way. The most frequent functional groups are hydroximates and catechols, in which the distances among the groups involved are optimal to bind iron. Siderophore concentrations in soil are approximately around 10^{-30} M. Iron is an essential nutrient for plants as it acts as a cofactor in a number of enzymes essential to important physiological processes such as respiration, photosynthesis and nitrogen fixation, so its deficiency is exhibited in severe metabolic modifications. Iron is quite abundant in soils but is frequently unavailable for plants or soil microorganisms. Predominantly, Fe^{+3} is the oxidized form that forms insoluble oxides and hydroxides inaccessible to plants and microorganisms. Plants thus have developed two strategies for efficient iron absorption: (1) releasing organic compounds capable of chelating iron, thus rendering it soluble where it diffuses towards the plant and gets reduced and absorbed by means of an enzymatic system present in the cell membrane of the plant, and (2) absorbing the complex formed by the organic compound and Fe^{+3}, where the iron is reduced inside the plant and readily absorbed. Several rhizobacteria release iron-chelating molecules into the rhizosphere and hence serve to attract iron towards the rhizosphere where it can be absorbed by the plant (Payne 1994). Siderophore-producing bacteria usually belong to the genus *Pseudomonas* (Haas and Défago 2005). Rhizosphere bacteria release these compounds to increase their competitive potential, since these substances have an antibiotic activity and improve iron nutrition for the plant (Glick 1995). Siderophore-producing rhizobacteria improve plant health at various levels; they improve iron nutrition, inhibit the growth of other microorganisms with the release of their antibiotic molecule, and hinder the growth of pathogens by limiting the iron available for the pathogen, generally fungi, which are unable to absorb the iron–siderophore complex (Shen et al. 2013).

Rhizobacterial Chitinase and Glucanase Production

Cell wall-degrading enzymes such as β-1,3-glucanase, chitinase, cellulase and protease secreted by biocontrol strains of PGPR exert a direct inhibitory effect on the hyphal growth of fungal pathogens by degrading their cell wall. Chitinase degrades chitin, an insoluble linear polymer of β-1,4-N-acetyl-glucoseamine, which is the major component of the fungal cell wall. The β-1,3-glucanase synthesized by strains of *Paenibacillus* and *Streptomyces* spp. can easily degrade fungal cell walls of pathogenic *F. oxysporum* (Compant et al. 2005). Similarly *Bacillus cepacia* synthesizes β-1,3-glucanase, which destroys the cell walls of the soilborne pathogens *R. solani*, *P. ultimum* and *Sclerotium rolfsii*. Potential biocontrol agents with chitinolytic activities include *B. licheniformis*, *B. cereus*, *B. circulans*, *B. subtilis* and *B. thuringiensis* (Sadfi et al. 2001). Among the Gram-negative bacteria, *Serratia marcescens*, *Enterobacter agglomerans*, *Pseudomonas aeruginosa* and *P. fluorescens* have been found to possess chitinolytic activities (Neiendam-Nielsen and Sørensen 1999). Cell wall-degrading enzymes of rhizobacteria affect the structural integrity of the walls of the target pathogen. A potent biocontrol strain of *Serratia marcescens* B2 induces chitinolytic and antifungal activities against soilborne pathogens *Rhizoctonia solani* and *Fusarium oxysporum*. The mycelia of the fungal pathogens co-inoculated with this strain showed various abnormalities such as partial swelling in the hyphae and at the tip, hyphal curling or bursting of the hyphal tip. The protection from phytopathogenic infection is a result of cell wall-degrading enzyme activities. The production of these enzymes by PGPR thus can categorize them as biocontrol agent against fungal pathogens.

Rhizobacterial Antibiotic Production

Utilization of microbial antagonists against plant pathogens in agricultural crops is an alternative available to chemical pesticides. PGPRs belonging to *Bacillus* and *Pseudomonas* species play an active role in the suppression of pathogenic microorganisms producing antibiotics. These bacterial antagonists enforce suppression of plant pathogens by the secretion of extracellular metabolites that are inhibitory even at low concentration. Bacteria belonging to *Bacillus* genus produce a wide variety of antibacterial and antifungal antibiotics. Some of these compounds including subtilin, subtilosin A, TasA and sublancin are well known and are derived from ribosomal origin, but others, such as bacilysin, chlorotetain, mycobacillin, rhizocticins, bacillaene, difficidin and lipopeptides belonging to the surfactin, iturin and fengycin families, are formed by non-ribosomal peptide synthetases (NRPSs) and/or polyketide synthases (PKS) (Leclere et al. 2005). The model organism *B. subtilis* 168 and the plant root-colonizing *B. amyloliquefaciens* FZB42 produce a wide variety of antibacterial and antifungal antibiotics, and their gene clusters involved in antibiotic biosynthesis have been identified. In *B. amyloliquefaciens* FZB42, the nine gene clusters (srf, bmy, fen, nrs, dhb, bac, mln, bae, dfn) direct the synthesis of bioactive peptides and polyketides by the enzymes NRPSs and PKS. Antibiotics are also produced by strains of *Pseudomonas* where *Pseudomonas fluorescens* and *Pseudomonas aeruginosa* are thoroughly studied. Antibiotics produced by these strains include 2,4 diacetyl phloroglucinol (DAPG), phenazine-1-carboxylic acid (PCA), phenazine-1-carboxamide (PCN), pyoluteorin (Plt), pyrrolnitrin (Prn), oomycin A, viscosinamide, butyrolactones, kanosamine, zwittermycin A, aerugine, rhamnolipids, cepaciamide A, ecomycins, pseudomonic acid, azomycin, antitumor antibiotics FR901463, cepafungins and antibiotic karalicin. These antibiotics are

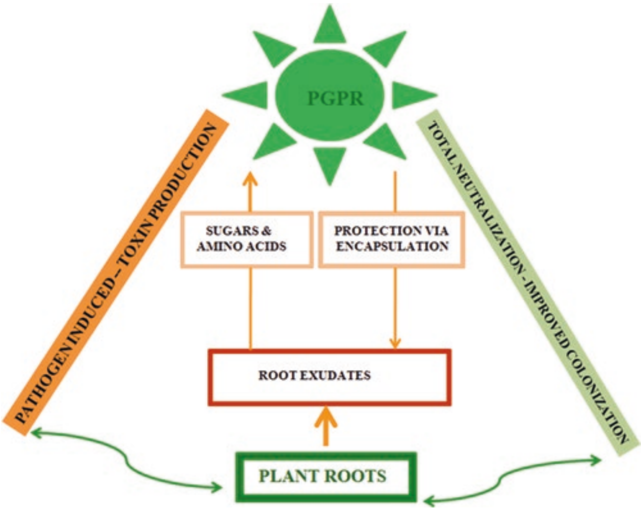

Fig. 7 Plant growth-promoting rhizobacterial interaction with plant root exudates, pathogens and other beneficial microbes in the rhizosphere

known to possess antiviral, antimicrobial, insect and mammalian antifeedant, antihelminthic, phytotoxic, antioxidant, cytotoxic, antitumor and PGP activities (Hammer et al. 1997). Other than the mentioned PGPR traits, functions carried out by these organisms in the rhizosphere are shown in Fig. 7. Briefly, PGPR eludes soil salinization/acidification by increasing the pH and producing capsular envelope to protect itself. PGPR alters root exudates either directly or indirectly through other beneficial microbes like arbuscular mycorrhizal (AM) fungi, thereby facilitating root colonization. PGPRs improve root colonization by undergoing phase variation. Toxins produced by roots and soil-inhabiting pathogens can also be degraded by PGPR (Dutta and Podile 2010).

Osmotolerance Induction by PGPR: The Mechanism

Plant growth-promoting bacteria colonize the rhizosphere of plants and facilitate growth of the plants, through various consequences within the plant as well as in the rhizosphere under saline conditions (Fig. 8). The direct promotion of plant growth by plant growth-promoting bacteria generally entails facilitating the acquisition of nutrient resources from the environment including fixed nitrogen, iron and phosphate or modulating plant growth by altering plant hormone levels such as auxin, cytokinin and ethylene. They induce indirect plant growth promotion by decreasing or preventing some of the deleterious effects of plant pathogen (usually a fungus) by any of one of several different mechanisms (Glick 2012). PGPRs alter the selectivity for Na^+, K^+ and Ca^{2+} resulting in higher K^+/Na^+ ratios (Fig. 8). They also render

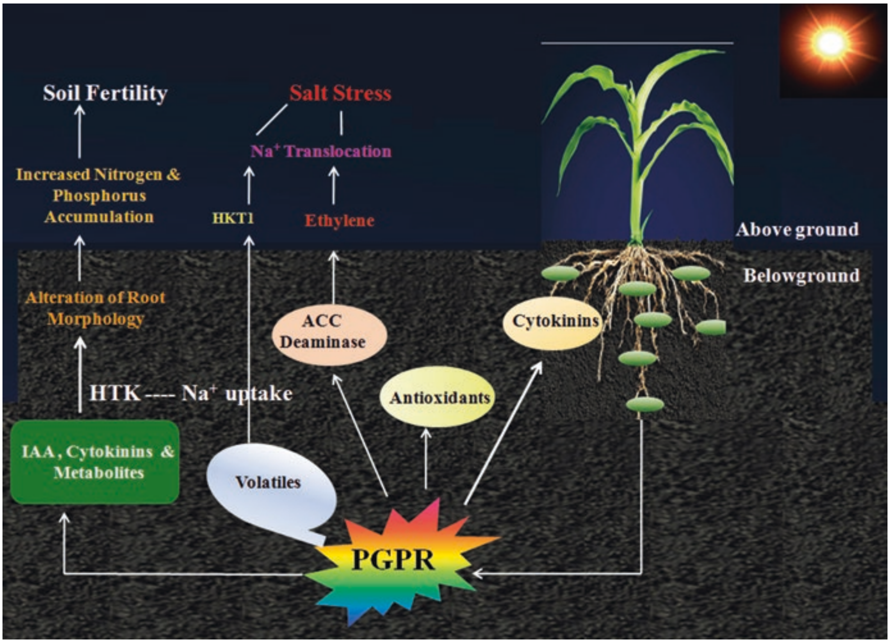

Fig. 8 Plant growth-promoting bacteria colonizing the rhizosphere for facilitating plant growth

production of bacteria-produced osmolytes, such as glycine betaine, which act synergistically with plant osmolytes and accelerate the osmotic adjustments. They cause changes in the membrane phospholipid content and alter the saturation pattern of the lipids, leading to reduction in membrane potential. Simultaneously, they promote the lateral root growth in plants through production of nitric oxide and indole-3-acetic acid (IAA) resulting in increased root surface area. They induce signalling cascades that put the stressed plants in a 'primed' physiological state into induced systemic resistance (ISR). Along with this, production of bacterial 1-amin ocyclopropane-1-carboxylic acid (ACC) deaminase activity reduces 'stress ethylene' levels within the plant, protecting the plant for salinity (Fig. 9).

Plant growth-promoting rhizobacterial effects on plants under salinity, bacteria involved and the plant species tested till date have been summarized in Table 2. Common adaptation mechanisms of plants exposed to salinity stresses include water and nutrient deficiency, changes in root morphology and process wherein production of phytohormones occurs. Indole-3-acetic acid (IAA) is produced in the plant shoot and transported basipetally to the root tips, where, at low concentrations, they enhance cell elongation, resulting in enhanced root growth. IAA promotes the initiation of lateral roots. However, higher concentrations of IAA in the root tips are an inhibitory effect on root growth. This inhibition is either direct or indirect through promotion of ethylene production (Glick 2012). Promotion of root growth results in a larger root surface and can, therefore, have positive effects on water acquisition

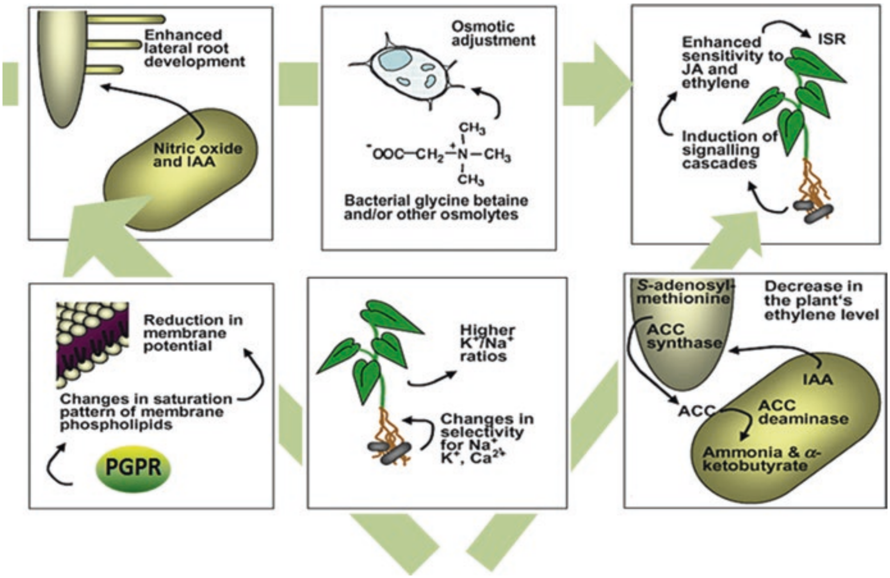

Fig. 9 Plant growth-promoting bacterial induced salinity stress tolerance within the plant-probable mechanics

Table 2 PGPR-induced salt tolerance in crops

Salt-tolerant PGPR	Crop species	Reference
Azospirillum brasilense	Pea (*Pisum sativum*)	Dardenelli et al. (2008)
Pseudomonas syringae, Pseudomonas fluorescens, Enterobacter aerogenes	Maize (*Zea mays*)	Nadeem et al. (2007)
Pseudomonas fluorescens	Ground nut (*Arachis hypogaea*)	Sarvanakumar and Samiyappan (2007)
Azospirillum	Lettuce (*Lactuca sativa*)	Barassi et al. (2006)
Achromobacter piechaudii	Tomato (*Lycopersicon esculentum*)	Mayak et al. (2004)
Aeromonas hydrophila/caviae *Bacillus insolitus* *Bacillus* sp.	Wheat (*Triticum aestivum*)	Ashraf et al. (2004)
Azospirillum	Maize (*Zea mays*)	Hamdia et al. (2004)
Azospirillum brasilense	Chickpeas (*Cicer arietinum*) Fava beans (*Vicia faba* I.)	Hamaoui et al. (2001)

and nutrient uptake. The availability of specific substrates as precursors for phytohormones, such as L-tryptophan for IAA, therefore, is a major factor determinant for bacterial stimulation of plant growth. Majority of root-associated bacteria, thus, displays beneficial effects on plant growth through production of IAA and has resulted in increased root growth and/or enhanced formation of lateral roots and root. Another widespread characteristic of rhizosphere bacteria is ACC deaminase activities regulation, which is a principal mechanisms by which bacteria exert beneficial effects on salinity stressed plants (Saleem et al. 2007). Bacteria possessing this enzyme use the immediate ethylene precursor ACC as a source of nitrogen. Bacterial hydrolysis of ACC leads to a decrease in plant ethylene level, which, in turn, results in increased root growth (Glick et al. 1998). Nevertheless, changes in root morphology are not the only consequence of bacterial ACC deaminase activity, as bacterial nitric oxide has also been implicated. For instance, in *Azospirillum*-mediated changes in root morphology with decreased level of ethylene alters the general stress status of the plant, as ethylene plays a key role in stress-related signal transduction pathways. Its synthesis increases when the plant is exposed to different types of stress. Like ethylene, proline is often synthesized by plants in response to various abiotic, as well as biotic stresses, mediating osmotic and free radical adjustment.

PGPR-Mediated Plant Root Proliferation and Plant Vigour

PGPRs colonize the rhizosphere of plants and promote growth of plants through root proliferation (Paul and Sarma 2006) as demonstrated by PGPR strain, *P. fluorescens* IISR-6, that significantly enhanced the root biomass of black pepper vines. Rhizobacteria-mediated root proliferation has been well proven in stressed soils (Diby et al. 2005a) indicating that a fruitful strategy for alleviating negative effects of salt stress in plants might be the co-inoculation of seeds with different PGPR species. Inoculation of various plant species with PGPRs has also been reported to lead to enhanced formation of lateral roots and root hairs that can result in enhanced tolerance to abiotic stress. Paul and Nair (2008) reported the root colonization potential of the salt-tolerant *Pseudomonas* strain was not hampered with higher salinity in soil. Promotion of root growth resulting in a larger root surface can, therefore, have positive effects on water acquisition and nutrient uptake (Diby et al. 2005b; Paul and Sarma 2006) that is expected to alleviate the stress effects in the plant. In addition, Kohler et al. (2009) reported that when lettuce plants were inoculated with PGPRs, they were more hydrated than control plants under saline conditions. Greater hydration induced by the PGPR strain is attributable to increased water use efficiency. Mayak et al. (2004) reported that when tomato plants were root bacterized with a suspension of beneficial bacteria, the extent of growth suppression due to salt stress was decreased, and the bacteria-treated plants accumulated more fresh and dry weights than untreated plants. Fu et al. (2010) observed that, with increasing salt concentration, growth of eggplant was progressively inhibited, but when the plants were inoculated with the PGPR *Pseudomonas* sp. DW1, the extent of growth suppression was decreased and these treated plants had greater dry weights than untreated plants, indicating the beneficial role of rhizobacteria in alleviating the debilitating effects of salt stress. Furthermore, PGPRs have also been reported to help seed germination in stressed soils. Barassi et al. (2006) reported the same in *Azospirillum*-inoculated lettuce seeds under salt stress. Applications of bio-priming of radish with PGPR strains significantly improved the percentage of seed germination under saline conditions (Kaymak et al. 2009). *Azotobacter* strains enhanced chlorophyll content in maize, revealing a positive effect on growth and plant development (Rojas-Tapias et al. 2012). Also in maize and canola, the rhizobacterial treatment increased the total chlorophyll contents (a, b and carotenoids) (Glick et al. 1998; Nadeem et al. 2007). The increase in chlorophyll content was result of an increased photosynthetic leaf area of the plant by rhizobacteria inoculation (Nadeem et al. 2007; Marcelis and Van Hooijdonk 1999). Pepper plants accumulated higher plant dry matter accumulation under salinity with *A. brasilense* and *Pantoea dispersa*, due to higher source activity induced by higher stomatal conductance and photosynthesis than non-inoculated plants, without affecting chlorophyll concentration or photosystem II photochemical efficiency.

PGPR Act as Sink for 1-Aminocyclopropane-1-Carboxylate (ACC)

Under salt stress soils, 1-aminocyclopropane-1-carboxylate (ACC) levels increase in plants, resulting in high ethylene concentration that ultimately increases plant damage (Botella et al. 1997). Chemical inhibitors of ethylene synthesis, such as cobalt ions and amino-ethoxy-vinyl glycine, are often used to overcome the problems associated with salt stress. However, these chemicals are not only expensive but also have harmful effects on environment (Dodd 2009). Rhizobacteria hydrolyze 1-amino cyclopropane-1-carboxylate to ammonia and a-ketobutyrate and thereby lower the ethylene levels in stressed plants and act as a sink for ACC (Saleem et al. 2007). In the presence of 1-aminocyclopropane-1-carboxylate deaminase producing bacteria, plant 1-aminocyclopropane-1-carboxylate is sequestered and degraded by bacterial cells to supply nitrogen and energy (Mayak et al. 2004), facilitating plant growth under the salinity stress condition (Siddikee et al. 2010). Furthermore, by removing 1-aminocyclopropane-1-carboxylate, the bacteria reduce the deleterious effect of ethylene, ameliorating plant stress and promoting plant growth (Glick et al. 2007). Mayak et al. 2004 have reported the effectiveness of 1-amino cyclopropane-1-carboxylate deaminase containing rhizobacteria for enhancing salt tolerance and consequently improving the growth of tomato, rice and various other crops under salt stress conditions. Halotolerant strains of bacteria from different bacterial genera, i.e. *Bacillus*, *Brevibacterium*, *Planococcus*, *Zhihengliuella*, *Halomonas*, *Exiguobacterium*, *Oceanimonas*, *Corynebacterium*, *Arthrobacter* and *Micrococcus* isolated from coastal soils, enhance plant growth under saline stress via 1-aminocyclopropane-1-carboxylate deaminase activity (Siddikee et al. 2010). The enzyme 1-aminocyclopropane-1-carboxylate deaminase has been found in a wide range of other rhizobacteria such as in *Achromobacter*, *Acidovorax*, *Alcaligenes*, *Enterobacter*, *Klebsiella*, *Methylobacterium*, *Pseudomonas*, *Rhizobium and Variovorax.*

PGPR-Induced Ion Homeostasis

PGPRs alter root uptake of toxic ions and nutrients by altering host physiology or by directly reducing the foliar accumulation of toxic ions (Na^+ and Cl^-) and improving the nutritional status of both macro- (N, P and K) and micronutrients (Zn, Fe, Cu and Mn). Potassium plays a key role in plant-water stress tolerance through being the cationic solute responsible for stomatal movements in response to changes in bulk leaf water status (Caravaca et al. 2004). *B. subtilis GB03* mediated the salt tolerance levels in *Arabidopsis thaliana* through regulation of the potassium transporter HKT1 (Zhang et al. 2008). Certain volatiles emitted by PGPR downregulate HKT1 expression in roots and upregulate it in shoots, orchestrating lower Na^+ levels and recirculation of Na^+ in the whole plant under salt conditions (Zhang et al. 2008). Rhizobacteria, thus, mediate the expression of an ion high-affinity K^+ transporter (AtHKT1) in *Arabidopsis* under saline conditions. PGPR inoculation in plants increases K^+ concentration, which in turn results in a high K^+/Na^+ ratio leading to their effectiveness in salinity tolerance (Kohler et al. 2009; Nadeem et al. 2013; Rojas-Tapias et al. 2012). *Azospirillum* could restrict Na^+ influx into roots and induce high K^+/Na^+ ratios in salt-stressed maize, where selectivity for Na^+, K^+ and Ca^{2+} was altered in favour of the plant (Hamdia et al. 2004; Ashraf et al. 2004). Salinity not only reduces Ca^{2+} and K^+ availability in plants but also reduces Ca^{2+} and K^+ mobility and transport to the growing parts of plants. However, *Pseudomonas* significantly increased Ca^{2+} in shoots of eggplants under saline conditions (Fu et al. 2010). PGPRs significantly increased the cotton's absorbability of Mg^{2+} and Ca^{2+} and decreased the absorption of the Na^+ (Yao et al. 2010). Ca^{2+} plays a major role as an early signalling molecule at the onset of salinity. Salt stress leads to damage to the plant cell membrane and hence increase its permeability resulting in electrolyte leakage and accumulation of it in the surrounding tissues. *Rhizobium* and *Pseudomonas* in *Zea mays* have lowered the electrolyte leakage (Bano and Fatima 2009; Sandhya et al. 2010). Similar observations made in *Arachis hypogaea* have suggested that PGPRs protect the integrity of the plant cell membrane from the detrimental effect of salt (Shukla et al. 2012).

PGPR-Induced Osmolyte Accumulation

Maintenance of water homeostasis and the functioning of photosynthetic structures are essential for alleviating the impacts of salinity on plant growth and crop yield. The most common stress responses in plants are overproduction of different types of compatible organic solutes such as proline and glycine betaine. Proline accumulation is a sensitive physiological index of the response of plants to salt and other stresses (Peng et al. 2008) for maintaining higher leaf water potential during stress and keeping plants protected against oxidative stress. PGPRs enhance plant stress tolerance by contributing to proline accumulation in plants. Increased accumulation of proline in soybean plants under saline conditions, through PGPR inoculation, not only alleviated salinity stress but also improved growth (Han and Lee 2005).

Azospirillum could also accumulate proline in plants as an osmoprotectant (Bashan 1999; Casanovas et al. 2003a, b). Proline protects higher plants against salt/osmotic stresses, by adjusting osmotic pressure and stabilizing many functional units such as complex II electron transport and enzymes like RuBP carboxylase/oxygenase (RUBISCO) (Makela et al. 2000). Proline also alleviates salt stress by helping the plant cells through stabilizing subcellular structures such as membranes and proteins, scavenging free radicals as well as buffering cellular redox potential (Ashraf and Foolad 2007; Kohler et al. 2009). Increase in total soluble sugars (TSS) of plants under salinity stress is another important defence strategy to cope with salinity stress. Increased proline and total soluble sugar in the PGPR-treated wheat plants significantly contributed to their osmotolerance (Upadhyay et al. 2012). Similarly, trehalose metabolism in rhizobia too seems important for improving plant growth, yield as well as adaptation to abiotic stress in leguminous plants.

PGPR-Induced Enhanced Antioxidative System

Salt shock in plants induces formation of reactive oxygen species, damaging lipids, protein and nucleic acids. Reactive oxygen species production is favoured due to over-reduction of photosynthetic electron chain by the limiting of photosynthesis (Johnson et al. 2003; Hichem et al. 2009). Antioxidants provide greater resistance to this oxidative damage (Spychalla and Desborough 1990). PGPRs enhance the antioxidative system through increased enzyme activities of catalase, guaiacol peroxidase and superoxide dismutase (Mittova et al. 2002). Significant increase in plants of several plant defence-related enzymes, superoxide dismutase, peroxidase, catalase, polyphenol oxidase, phenylalanine ammonia-lyase, lipoxygenase and phenolics, through PGPRs has been reported (Nautiyal et al. 2008). These PGPR-induced antioxidative enzymes alleviate salt stress in plants by eliminating hydrogen peroxide from salt-stressed roots. Bacterial extracellular polymeric substance is produced during plant stress alleviation. Extracellular polymeric substance-producing PGPR significantly enhances the volume of soil macropores and the rhizosphere soil aggregation, resulting in increased water and fertilizer availability to inoculated plants, which in turn helps plants to better manage the salt shock. They also influence the aggregation of root-adhering soils and bind cations including Na^+ thereby decreasing their toxicity (Upadhyay et al. 2011; Alami et al. 2000). The extracellular polymeric substance of bacteria possesses unique water holding and cementing properties, playing a vital role in the formation and stabilization of soil aggregates and regulation of nutrients and water flow across plant roots through biofilm formation (Roberson and Firestone 1992).

PGPR-Induced Enhanced Nutrients Uptakes

Salinity stress-induced nutritional imbalance hampers plant growth and development and affects the crop performances adversely. Nutrient uptake by plants greatly affects their ability to adapt to salinity stress; any impairment exacerbates the adverse effects of salt shocks. Imbalances generally result from poor nutrient availability, competitive uptake, transport or partitioning within the plant or are caused by physiological inactivation of a given nutrient, resulting in an increase in the plant's internal requirement for that essential element (Grattan and Grieve 1994). These then reduce NPK uptakes and decreases phosphorus accumulation in crops (Sharpley et al. 1992). PGPRs play a vital role for circulation of plant nutrients and affect the plant growth directly by solubilizing inorganic phosphate, improving nutrient uptake and mineralizing organic phosphate (Dobbelaere et al. 2003). Rhizobacteria transfer P from poorly available forms and play an important role in maintaining P in readily available pools, thereby increasing their availability to the host plant and improving their growth (Rashid et al. 2004). Enhanced nutrient mobilization in the rhizosphere of black pepper and significant uptake of nitrogen (N) and phosphorus (P) in the PGPR-treated black pepper vines resulted in root proliferation and enhanced plant growth (Diby et al. 2005b). Efficient rhizobacteria strains having phosphorus-solubilizing ability even under high saline (60 g L^{-1} NaCl) conditions have improved growth (Son et al. 2006; Upadhyay et al. 2011). The damaging effects of NaCl on wheat seedlings were reduced by inoculation with *A. brasilense*. *Azospirillum* inoculation in lettuce seeds improved the germination and vegetative growth after being exposed to NaCl and caused an extended exudation of plant flavonoids contributing to relief from salt stress (Barassi et al. 2006).

PGPR-Mediated Disease Suppression

In general, salinity weakens the defence system that further aggravates the shocks to the plants. Under such circumstances, the plants are affected by diseases, and they begin to compete for nutrients and niche exclusion. The chief modes of mechanism to control these diseases are induced systemic resistance (ISR) and antifungal metabolites production (Lugtenberg and Kamilova 2009). Induced systemic resistance is the enhanced defensive capacity that a plant develops against a broad spectrum of plant pathogens after colonization of the roots by certain strains of microorganisms (van Loon et al. 1998). It involves jasmonate and ethylene signalling within the plant, and these hormones stimulate the host plant's defence responses against a variety of plant pathogens (Glick 2012). Several rhizobacteria produce antifungal metabolites like HCN, phenazines, pyrrolnitrin, 2,4-diacetylphloroglucinol, pyoluteorin, viscosinamide and tensin and have exhibit biological control of plant pathogens under saline soils. Increasing salinity reported that the population of the biocontrol agent, *P. fluorescens*, in the saline rhizospheric soil did not change, indicating that the colonization efficiency of the strain was not affected by the salinity factor. The osmotolerance mechanisms of the salt-tolerant PGPRs effectively nullified the detrimental effects of high osmolarity and fully serve as biocontrol agents in crops grown in saline soils (Paul and Nair 2008). Salt-tolerant *P. chlororaphis* strain repressed root rot caused by *F. solani* in cucumber and tomato under salinated soil (Egamberdieva 2012).

PGPR-mediated biocontrol of several crop diseases against an array of pathogens under saline conditions have been reported (Elmer 2003; Paul and Nair 2008; Rangarajan et al. 2003; Triky-Dotan et al. 2005). Several species of PGPRs with strong activity and microbial components such as lipopolysaccharides, flagella, siderophores, cyclic lipopeptides, 2,4-diacetylphloroglucinol, homoserine lactones and certain volatiles have been reported as elicitors of induced systemic resistance (Lugtenberg and Kamilova 2009). Induced systemic resistance in plants by rhizobacteria has been proven against several bacterial, fungal and viral plant diseases. *B. subtilis* GB03, a commercial biocontrol agent, induces systemic tolerance to salt stress in *Arabidopsis* (Zhang et al. 2008), and some volatile organic compounds emitted are believed to be bacterial determinants involved in induced systemic tolerance (Ryu et al. 2004).

4 Future Prospects: Sustaining Shining Saline Agriculture

Salinity is posing serious threat to agriculture, biodiversity and the environment. And as the saline areas under agriculture are increasing every year across the globe, it is of much public concern. It is not only suppressing the plant growth but is also disturbing the sustainability of beneficial microorganisms associated with the plant rhizosphere. As a result, there is a growing worldwide demand for sound, ecologically compatible and environmentally friendly techniques in saline soil agriculture. Over the period of last 40 years, PGPRs have shown promises to support sustainable agriculture. Application of PGPRs is thus an important alternative to some of the traditional agricultural techniques, and it is now widely in practice. PGPRs that live in association with plant roots alleviate salt stress for better growth and yield, through their own mechanisms for osmotolerance, osmolyte accumulation, asymbiotic N_2 fixation, solubilization of mineral phosphate and other essential nutrients, enhanced NPK uptakes, production of plant hormones, ACC production, scavenging ROS, ISR and IST. Summary of overall mechanics employed by PGPR is portrayed in Fig. 10. The potential PGPR isolates are being formulated using different organic and inorganic carriers either through solid or liquid fermentation technologies. Along with this, the use of PGPR consortium with known functions that could act synergistically is being exploited, as they offer multiple modes of action, temporal or spatial variability. However, despite such lengthy research over the period of several decades, potentials for appropriate utilization of PGPRs remain unfolded and unexplored. Researchers though have begun to develop a much more complex and detailed understanding of PGPR mechanics; lot of hard work is waiting to focus on their integration with conventional breeding programmes and agronomical instruments, before they can lead to sustainable shining saline agriculture.

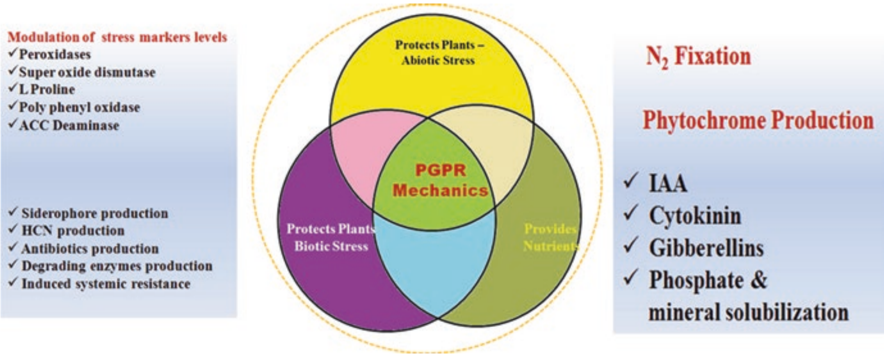

Fig. 10 Schematic diagram representing plant growth-promoting bacterial mechanics

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Arbuscular Mycorrhizal Fungi (AMF) for Sustainable Soil and Plant Health in Salt-Affected Soils

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1 Introduction

Soil salinity is a serious problem for crop growth and productivity and is increasing day by day throughout the world particularly in arid and semiarid areas. The extent of salt-affected soils is highest in Asia Pacific region including Australia. Countries like Argentina, Australia, China, Egypt, India, Iran, Iraq, Pakistan, Thailand, former Soviet Union and USA are predominantly affected by soil salinization. Salt-affected soils are occupying about 7 % of the earth's land surface (Ruiz-Lozano and Azcón 2000) and about 5 % of the total cultivated land around the world, i.e. 1.5 billion hectares (Sheng et al. 2008). It is anticipated that the increased salinization of arable land will result in to 50 % land loss by the middle of the twenty-first century (Wang et al. 2003). Consequently, the total salt-affected area (6.74 mha) is likely to increase to 16.2 mha by 2050. Secondary salinization, dry land salinity, coastal salinity and sea water ingress are the major cause of concern in salt-affected regions in different continents. Since the nature and properties of the problem soils are diverse, specific approaches are needed to reclaim and manage these soils to maintain their long-term productivity. Continuous utilization of good quality land and water resources in the domestic and industrial sectors has already generated enhanced interest in the utilization of salt-affected soils and poor quality waters. Excessive seepage, ingress of sea water, aridity, excessive water use, faulty irrigation practices, pedogenic sources,

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saline water irrigation, wind-blown salt, capillary rise from shallow water table, etc., are the probable reasons for saline soils. In general, three categories of salinity effects have been considered for low plant productivity: (1) general growth suppression due to a low osmotic potential especially during germination, emergence and early seedling growth (Maas and Hoffman 1977; Maas et al. 1983; Marschner 1995), (2) growth suppression caused by toxicity of specific ions (Maas 1986) and (3) growth suppression due to nutritional imbalance of essential ions (Munns and Termant 1986). Often, these different effects are indistinguishable and, in fact, the primary cause of salinity damage is not known. The effects of salinity/sodicity on plants are thus quite complicated and inseparable in some cases. Overall, salinity leads to many detrimental effects on plants and that at different life stages. Many strategies were proposed to overcome salt detrimental effects such as development of new salt-tolerant crops trough breeding or genetic engineering (Tang et al. 2005; Wu et al. 2005; Wei-Feng et al. 2008), removing excessive salt accumulation in groundwater and desalinizing water for irrigation (Ashraf and Harris 2004; Flowers 2004; Zhang and Blumwald 2001). Although these strategies appear efficient, yet they are costly and out of reach for developing countries that are the most affected. Hence, a new alternative attempt has taken up to tackle the deleterious effects of saline soils which involve inoculation of salt-tolerant arbuscular mycorrhizal fungi (AMF) in agricultural crop.

These specialized fungi colonize plant roots and extend far into the soil. More than 90 % of plant species in natural areas form a symbiotic relationship with the beneficial mycorrhizal fungi. The plant supplies carbohydrate to the fungi, while the mycorrhizal fungi extend the surface area of the plant's roots and thus increase their ability to absorb more nutrients and water from the soil.

AMF maintain physiological and biochemical processes of the host plant (Augé 2000; Ruiz-Lozano 2003). In salt-stressed soil, phosphate ions usually precipitate along with Ca^{2+}, Mg^{2+} and Zn^{2+} and are less available to plants (Azcón-Aguilar et al. 1979). But, AMF symbiosis in plants enhances the uptake of less mobile phosphorus by extending their external hyphal network beyond nutrient depletion zone. In mitigation of salt stress, AMF also improve plant growth and hormonal status, increase nutrient acquisition, maintain osmotic balance, reduce ion toxicity, etc. (Juniper and Abbott 1993; Lindermann 1994; Ruiz-Lozano 2003). It also provides a stable soil for plant growth via production of glomalin—a substance that binds soil aggregates (Wright and Upadhyaya 1998). In this chapter we have discussed the role of AMF in amelioration of salt-affected soils and the mechanism of salt tolerance in AMF-plant symbiosis.

2 Effects of Salt Stress on Plant Growth and Nutrient Uptake

Salinity causes both ionic and osmotic imbalance on plants and most of the known responses to salinity are linked to these effects. The general response of plants to salinity is reduction in growth (Romero-Aranda et al. 2001; Ghoulam and Foursy

2002). The initial and primary salinity, especially at low to moderate salt concentrations, is due to osmotic effects (Munns and Termant 1986). Osmotic effects of salts on plants are as a result of lowering water potential due to increased solute concentration in the root zone. Thus, in some species salt stress may resemble drought stress. However, at low or moderate salt concentration, plants adjust osmotically and maintain a potential for the influx of water (Günes et al. 1996; Ghoulam and Foursy 2002). At high salinity, some specific symptoms of plant damage may be recognized, such as necrosis and leaf-tip burn due to Na^+ or Cl^- ions. High ionic concentrations may disturb membrane integrity and function and interfere with internal solute balance and nutrient uptake, causing nutritional deficiency symptoms similar to those of drought (Grattan and Grieve 1999). The degree to which growth is reduced varies with species and to a lesser extent with varieties (Bolarin et al. 1991; Ghoulam and Foursy 2002). Salt accumulation in leaves causes premature senescence, reducing the supply of assimilates to the growing regions and thus decreasing plant growth (Munns 1993). Romero-Aranda et al. (2001) suggested that induced water stress occurs as a result of salt accumulation at the soil/root interface. This accumulation results in a lower total water potential (Ψp), bringing about substantial difficulties in water uptake by plants. As the concentration of the external solution becomes hypertonic, the plasma membrane separates from the cell wall and shrinkage of the protoplast occurs. The space between the plasma membrane and the cell wall is filled with the extracellular solution. The outcome of this stress is a decrease in water content. There are many evidences which indicate that primary effects of salinity take place in roots, and it is water deficit rather than specific ion toxicity (Munns and Termant 1986). According to Sohan et al. (1999) and Romero-Aranda et al. (2001), increase of salt in the root-zone medium can lead to a decrease in leaf water potential and may affect many plant processes. At very low soil water potential, this condition can interfere with plant's ability to extract water from the soil and maintain turgor (Sohan et al. 1999). Many authors reported that water and osmotic potential of plants became more negative with an increase in salinity, whereas turgor pressure increased (Meloni et al. 2001; Romero-Aranda et al. 2001; Gulzar et al. 2003). Most of the rapid responses in leaf elongation rate to substrate salinity are attributable to changes in leaf water status. The quantity of ions delivered to the shoot per root mass and time are a real measure of the plant's ability to adjust, and in *Suaeda maritima*, the rate of Na^+ transport was much greater than in some non-halophytes even at moderately high external concentrations.

High NaCl uptake competes with the uptake of other nutrient ions, such as K^+, Ca^{2+}, N and P, resulting in nutritional disorders and eventual reduction in yield and quality (Grattan and Grieve 1999). A number of studies have shown that salinity can reduce N accumulation in plants (Feigin et al. 1991; Pardossi et al. 1999; Silveira et al. 2001). In most cases, salinity decreased the concentration of P in plant tissues (Kaya et al. 2001), but in some studies, salinity either increased or had no effect on P uptake (Ansari 1990).

Salinity stress can cause an imbalance in the uptake of mineral nutrients and their accumulation within the plants (Grattan and Grieve 1994). Osmotic stress, ion imbalances, particularly with Ca^{2+} and K^+, and direct toxic effects of Na^+ and Cl^- ions on the metabolic processes are the most important and widely studied physiological impairments caused by salt stress (Munns 2002). Research revealed that salinity inhibits the growth of plants by affecting both water absorption and biochemical processes such as N and CO_2 assimilation and protein biosynthesis (Cusido et al. 1987). Under saline conditions plants fail to maintain the required balance of organic and inorganic constituents leading to suppressed growth and yield (Günes et al. 1996). Plant performance, usually expressed as a crop yield, plant biomass or crop quality (both of vegetative and reproductive organs), may be adversely affected by salinity-induced nutritional disorders. These disorders may be a result of the effect of salinity on nutrient availability, competitive uptake, transport or partitioning within the plant (Grattan and Grieve 1999; Zhu 2003; Ali et al. 2008; Nasim et al. 2008).

3 Effect of AMF on Plant Growth and Nutrient Uptake Under Salinity

"Mycor"-"rrhiza" literally means "fungus"-"root" and describes the mutually beneficial relationship between fungi and the roots of vascular plants. These specialized fungi, belong to the order Glomales, colonize plant roots and extend far into the soil. More than 90 % of plant species in natural areas form a symbiotic relationship with the beneficial mycorrhizal fungi. AMF associations are composed of three main structures. First, hyphae work as external filamentous arms searching for nutrients around the root zone (Hodge 2000). Second, there are specialized vesicles within the root, which are thought to be storage organs, especially for lipids (Hirsch and Kapulnik 1998). Arbuscules are the third important part of the AM association. They are branched intercellular structures, resembling trees, and are the main functional site of phosphorus and other nutrient exchange in the root system (Smith et al. 2000).

The plant supplies carbohydrate to the fungi, while the mycorrhizal fungi establish symbioses with roots. Thus it extends the surface area of the plant's roots and contributes to improving water use and uptake of less mobile nutrients like phosphorus, zinc and copper. Besides, these AMF also alter hormonal status of plants and increase plant tolerance to various biotic and abiotic factors (Smith and Read 1997). Thus, AMF can promote plant growth (Hirrel and Gerdemann 1980; Copeman et al. 1996) through improvement of plant nutrition and production of osmoregulators (Ojala et al. 1983; Duke et al. 1986; Ruiz-Lozano and Azcón 2000).

AMF that widely exist in salt-affected soils (Juniper and Abbott 1993) are considered as tolerant isolates. These AMF may have a higher ability to improve the survival and growth of host plants than species or isolates from normal edaphic condition. Many studies have demonstrated that inoculation with AMF improves growth of plants under a variety of salinity stress conditions (Ruiz-Lozano et al. 1996; Al-Karaki et al. 2001). To some extent, these fungi have been considered as bio-ameliorators of saline soils (Azcón-Aguilar et al. 1979; Singh et al. 1997; Rao

1998). Several researchers reported that inoculation with AMF improves growth of crops and plants under salt stress (Jindal et al. 1993; Yano-Melo et al. 2003; Giri and Mukerji 2004; Tian et al. 2004; Cho et al. 2006; Ghazi and Al-Karaki 2006; Sharifi et al. 2007; Beltrano et al. 2013). Higher plant growth rate was observed in AMF-inoculated banana (Yano-Melo et al. 2003), cotton (Tian et al. 2004), soybean (Sharifi et al. 2007), lettuce (Aroca et al. 2013), strawberry (Sinclair et al. 2014) and tomato (Latef and Chaoxing 2011; Balliu et al. 2015) than that of controls under saline condition. When AMF are inoculated in saline soils, there is high demand of energy for fungal survival and establishment, and once the fungus becomes effective, increasing nutrient uptake and host plant tolerance occur.

The improved growth of AMF inoculated plants has been attributed to enhanced acquisition of mineral nutrients such as P, Zn, Cu and Fe (Nelson and Safir 1982; Al-Karaki et al. 2001; Ghazi and Al-Karaki 2006). Mycorrhizal colonization improves plant growth under salinity that may be due to enhanced P uptake by AMF plants (Poss et al. 1985; Duke et al. 1986).

AMF-inoculated control plants also increased the uptake of phosphorous (P). The enhancement of plant P uptake by AMF has been considered one of the main reasons for amelioration of growth in salt-affected plants (Ruiz-Lozano and Azcón 2000; Giri et al. 2007). However, in some cases Plant tolerance to salt was not related to P concentration (Danneberg et al. 1992; Ruiz-Lozano et al. 1996). Under salinity conditions plants accumulate less potassium (K^+). But inoculation of AMF significantly improves concentration of K^+ in salinity condition. Higher K^+ accumulation by mycorrhizal plants in saline soil maintains high K^+/Na^+ ratio and ionic balance of the cytoplasm by influencing Na efflux from plants. The replacement of K^+ by Na^+ allows osmotic adjustment which may be the responsible factor. AMF lowers the Na^+ concentration than that of nonmycorrhizal plants regardless of salinity level (Giri et al. 2007). Increased salt tolerance in AMF-colonized plants is also influenced by the internal transport or storage of Na^+ or Cl^- ion (Al-Karaki 2000; Baker et al. 1995).

Potassium plays an important role in processes such as water balance, cell extension and solute transport in the xylem. Cell extension is the consequence of K^+ accumulation. Potassium is required for stabilizing pH in the cytoplasm and for increasing the osmotic potential in the vacuole of plant cells. Stomatal regulation is a major mechanism controlling the water regime in the plant which is also governed by K^+. In addition, potassium as osmotic solute is able to maintain a high tissue water level even under conditions of osmotic deficiency. In higher plants, K^+ affects photosynthesis at various levels. The role of K^+ in CO_2 fixation has been demonstrated, and an increase in the leaf potassium content is accompanied by increased rates of photosynthesis, photorespiration and RuBP carboxylase activity and a concomitant decrease in dark respiration. Enhanced respiration rates are a common feature of potassium deficiency (Bottrill et al. 1970). The degree of salt tolerance of mycorrhizal plants largely depends on K^+. The highest salt tolerance of mycorrhizal plants has the greatest K shoot concentration (Porras-Soriano et al. 2009).

4 AMF for Soil Health

Quality soil is critical for any sustainable development which is continuously decreasing due to rapid civilization and industrialization. The quality of soil depends not only on its physical or chemical properties but also on the diversity and activity of soil biota (Doran and Linn 1994).

AMF are major components of the soil microfauna and obviously interact with other microorganisms in the rhizosphere (Bowen and Rovira 1999). AMF develop intensively inside roots of plant and within the soil by forming an extensive extraradical network, and this improves mineral and water uptake capacity of plants from the soil. Thus, AMF symbiosis changes plant physiology as well as nutritional and physical properties of the rhizosphere soil. This, in turn, affects colonization patterns of this region by soil microorganisms by the so called mycorrhizosphere effect (Gryndler 2000). In the mycorrhizosphere, AMF interact with natural and introduced microorganisms and affect soil properties and quality (Fig. 1).

The extraradical hyphae of AMF act as a direct conduit for host C into the soil and contribute directly to its C pools, bypassing the decomposition process. As a consequence of this, the amount and activity of other soil biota are stimulated; however, this seems to be a selective phenomenon, since it stimulates in particular the microbes having antagonistic activity against soilborne pathogens (Linderman 2000). The reason for this phenomenon is unknown, but this observation clearly indicates that AMF could be useful biological tools for maintaining healthy soil systems.

Another important role of mycorrhizal fungal mycelium is in the formation of water-stable soil aggregates (Andrade et al. 1998; Bethlenfalvay et al. 1999; Miller and Jastrow 2000). Indeed, AMF produce a very stable hydrophobic glycoprotein, glomalin, which is deposited on the outer hyphal walls of the extraradical mycelium and on adjacent soil particles and which appears to act as a long-term soil-binding agent (Wright and Upadhyaya 1998, 1999). As a consequence, the extraradical

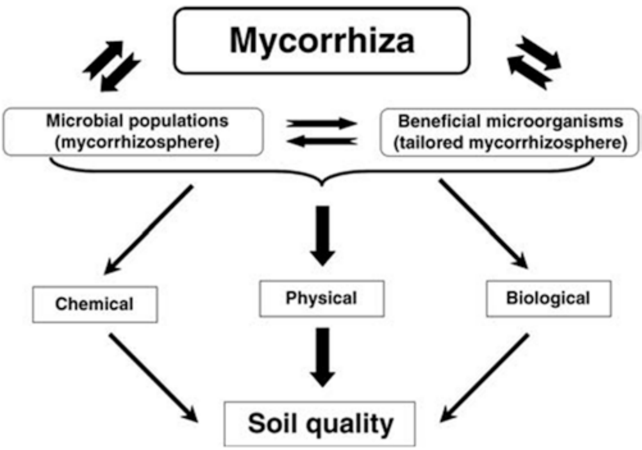

Fig. 1 Arbuscular mycorrhizal fungi interact with natural and introduced microorganisms in the mycorrhizosphere, thus affecting soil properties and quality (Source: Jeffries et al. 2003)

hyphae, together with the fibrous roots, can form a "sticky-string bag that contributes to the entanglement of soil particles to form macroaggregates," (Miller and Jastrow 2000) a basic building block of soil structure. Thus, AMF are essential components for maintaining soil structure in agricultural soils.

5 Mechanisms of Amelioration of Salt Stress in AMF-Plant Symbiosis

5.1 Morpho-physiological Alterations

Morphological and physiological characteristics of plants are keys to address any abiotic (salt) stress management, hence most integral part of such experiments. There are number of studies carried out to assess the role of AMF for alleviating the salt stress in crop plants, and most of them reported a positive outcome. Association of AMF showed beneficial effect on root morphology of *Citrus tangerina* seedlings and enhanced the characters like root length, root-projected area, root surface area and root volume under salinity (Wu et al. 2010). Mycorrhizal colonization also caused improvement in fruit fresh weight, fruit number and fruit yield of salt-stressed tomato plants (Al-Karaki 2000; Latef and Chaoxing 2011). Improved growth, yield and quality of fruits of *Cucurbita pepo* plants was also noticed when colonized by *Glomus intraradices* in salinity stress (Colla et al. 2008). Olive plants inoculated with *Glomus mosseae* helped to survive the plants better in salt-stressed condition in terms of enhanced root and shoot growth and lesser biomass reduction (Porras-Soriano et al. 2009). Among field crops, AMF-inoculated maize plants showed to have better root morphology (length, mass, surface area, diameter and volume) under imposition of salt treatments (Sheng et al. 2009).

5.2 Biochemical and Physiological Changes

Various studies have investigated to understand mechanisms for enhanced salt tolerance of AMF plants. These mechanisms include better ability for nutrient and water uptake due to an extended explored soil surface by fungal hyphae, greater root hydraulic conductivity and osmotic adjustment, maintenance of enhanced K^+/Na^+ ratios and lower accumulation of sodium in the shoots of the host plants (Fig. 2). Thus salt-stress alleviation by AMF results from a combination of nutritional, biochemical and physiological effects. In this section, we discuss our current knowledge of the regulation by AMF symbiosis of plant responses to salt stress and propose new perspectives for physiological and molecular studies, which should shed further light on the intimate tolerance mechanisms induced by AMF symbiosis.

Plant tolerance to salt itself is a complex trait to which many different factors may contribute. Plants have evolved biochemical and molecular mechanisms, which may act in a concerted manner and constitute the integrated physiological response to soil

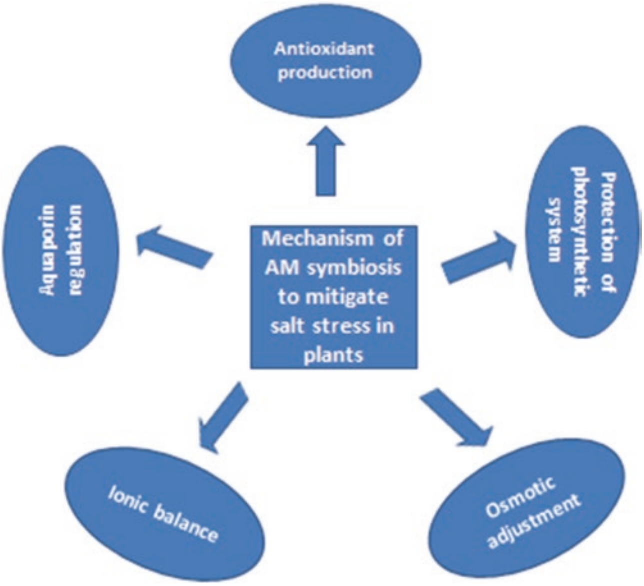

Fig. 2 Mechanisms of the AMF symbiosis which regulate the physiological plant responses in order to improve tolerance to salinity. The exchange flux of water, minerals (M) and carbon compounds (C) between the plant and AMF is also shown. Minerals include nutrients and salt ions present in the soil solution

salinity. The most important plant strategies are (1) synthesis and accumulation of compatible solutes; (2) control of ion uptake by roots, compartmentation and transport into plant tissues, which constitutes the ion homeostasis strategy; (3) fine regulation of water uptake and distribution to plant tissues by the action of aquaporins; and (4) reduction of oxidative damage through improved antioxidant capacity. Additional plant responses can include selective build-up or exclusion of salt ions, maintenance of photosynthesis at values adequate for plant growth, changes in membrane structure and synthesis of phytohormones (Turkan and Demiral 2009).

5.2.1 Osmotic Adjustment

Water potential of salt-accumulated soil becomes more negative. Thus, to avoid cell dehydration, plants must respond by decreasing their water potential in order to maintain a favourable gradient for water flow from the soil into the roots. Accumulation of some inorganic ions such as Na^+ and K^+ and compatible organic solutes, known as osmotic adjustment or osmoregulation is the most important mechanism to reduce plant osmotic potential (Morgan 1984; Hoekstra et al. 2001). The most important organic solutes include amino acids (proline), amide and proteins, quaternary ammonium compounds (glycine betaines) and polyamines, soluble sugars, pinitol and mannitol (reviewed by Ruiz-Lozano et al. 2012). Osmotic adjustment allows cells to maintain turgor and related processes, such as cellular expansion and growth, stomatal opening and photosynthesis, while keeping a gradient of water potential favourable to water entering the plant. Proline, glycine betaine, pinitol and mannitol are important osmoprotectant osmolytes that are synthesized by many plants in response to dehydration stresses, including salinity. Proline plays roles in stabilizing subcellular structures, in buffering cellular redox potential under stresses and in scavenging free radicals (Chen and Dickman 2005). Betaines can stabilize protein complexes and the structures and activities of enzymes, as well as maintaining the integrity of membranes against the damaging effects of salt stress (Evelin et al. 2009). The effects of salinity on various biochemicals on AMF plants are listed in Table 1.

Table 1 Biochemical compounds increased/decreased in various crops/plants under AMF symbiosis during salinity stress

Compound	Crop/plant	Fungus	Effect	References
Proline	*Glycine max* *Cyamopsis tetragonoloba* *Zea mays* *Lactuca sativa*	*Glomus mosseae* and *Glomus fasciculatum* *Glomus mosseae* *Glomus* spp.	Increase Decrease Decrease	Datta and Kulkarni (2014) Sheng et al. (2011) Ruiz-Lozano et al. (1996)
Glycine betaine	*Phragmites australis*	*Glomus fasciculatum*	Increase	Al-Garni (2006)
Polyamines	Lotus glaber	*Glomus intraradices*	Increase	Sannazzaro et al. (2007)
Carbohydrates	*Glycine max* *Cyamopsis tetragonoloba* *Vigna radiata*	*Glomus mosseae* and *Glomus fasciculatum* *Glomus clarum*	Increase Increase	Datta and Kulkarni (2014) Rabie (2005)
Chlorophyll	*Capsicum annuum* *Glycine max* *Cyamopsis tetragonoloba* *Zea mays*	*Glomus intraradices* *Glomus mosseae* and *Glomus fasciculatum* *Glomus mosseae*	Increase Increase Increase	Beltrano et al. (2013) Datta and Kulkarni (2014)
Abscisic acid	*Solanum lycopersicum* *Lactuca sativa*	*Glomus mosseae*, *Glomus intraradices* *Glomus etunicatum* *Glomus intraradices*	Reduce salt-induced increase Reduce	Abeer et al. (2015b) Aroca et al. (2013)
Auxin	*Solanum lycopersicum*	*Glomus mosseae*, *Glomus intraradices* *Glomus etunicatum*	Enhance salt-induced decrease	Abeer et al. (2015b)
Antioxidant enzymes	*Solanum lycopersicum* *Malus hupehensis* *Vigna unguiculata*	*Glomus mosseae* *Glomus versiforme* *Glomus mosseae*, *Glomus intraradices* and *Glomus etunicatum*	Increase Increase Increase	He et al. (2007) Yang et al. (2014) Abeer et al. (2015a)

So far, investigations carried out on osmoregulation in AMF symbiosis are scarce and somewhat contradictory. Several studies have reported a higher concentration of osmolytes in AMF plants than in non-AMF plants at different salinity levels (Jindal et al. 1993; Al-Garni 2006; Sharifi et al. 2007; Talaat and Shawky 2011), while, in contrast, other studies have reported that non-AMF plants accumulate more osmolytes than AMF plants under salt stress (Wang et al. 2004; Rabie and Almadini 2005; Jahromi et al. 2008; Sheng et al. 2011). These studies involve different plant species such as soybean, wheat, bean, lettuce and maize and different plant parts and also different AMF such as *Glomus intraradices*, *Glomus mosseae* or a mixture of *Glomus* spp. and even different treatments such as salt pretreated mycorrhizal fungi (Sharifi et al. 2007; Ruiz-Lozano et al. 2011), which may explain the contrasting results obtained. Thus results suggest that proline accumulation in plants may be due to salinity and not necessarily the result of mycorrhizal colonization or that proline accumulation may be a symptom of stress in less-salt-tolerant species.

5.2.2 Polyamines

Free polyamines are small organic cations that are necessary for eukaryotic cell growth. Putrescine (Put), spermidine (Spd) and spermine (Spm) are three main polyamines in plants. These cations are thought to play an important role in plant responses to a wide array of environmental stressors such as salinity (Delauney and Verma 1993; Krishnamurthy and Bhagwat 1989), high osmolarity (Besford et al. 1993) and antioxidative stress (Kurepa et al. 1998). They have been proposed as candidates for regulation of root development under saline situations (Couee et al. 2004). Polyamine-enhanced membrane stability has been shown to have a significant effect on both H^+/ATPase and Ca^{2+}/ATPase transporters during salinity stress (Roy et al. 2005; Pottosin and Shabala 2014). Inoculation of host plants with AMF increases free polyamine concentrations in plants under saline conditions. Free polyamine concentrations in plants generally reduced under saline conditions.

5.2.3 Antioxidants

Reactive oxygen species (ROS) such as singlet oxygen, superoxide anion (O_2-), hydrogen peroxide (H_2O_2) and hydroxyl radical (OH) are unavoidable byproducts of the interaction between oxygen and electrons leaked from the electron transport chains in chloroplast and mitochondria during normal aerobic metabolism (Scandalios 1993; Asada 1999). These radicals and their derivatives are among the most reactive species known to chemistry, capable of reacting indiscriminately to cause oxidative damage to biomolecules such as lipid peroxidation, denaturation of proteins and mutation of DNA (Bowler et al. 1992), and in the absence of the protective mechanism, they can damage cell structure and function (Alguacil et al. 2003). Plant cells have protective and repair mechanism to minimize the occurrence of oxidative damage, which include non-enzymatic molecules that act as ROS scavengers such as ascorbate, glutathione, a-tocopherol, flavonoids, anthocyanines and carotenoids, and specific ROS-scavenging antioxidative enzymes consist of superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APOX), glutathione reductase, dehydroascorbate reductase, monodehydroascorbate reductase, guaiacol peroxidase, oxidized glutathione, glutathione peroxidase and the enzymes involved in the ascorbate–glutathione cycle (Alguacil et al. 2003; Wu et al. 2006).

A correlation between antioxidant capacity and salinity tolerance has been documented in several plant species (Benavides et al. 2000; Núñez et al. 2003; Turkan and Demiral 2009). Further, several studies have suggested that AMF symbiosis helps plants to alleviate salt- or water-deficit stresses by enhancing the activities of antioxidant enzymes (Porcel et al. 2003; Ghorbanli et al. 2004; Zhong et al. 2007; Garg and Manchanda 2009; Talaat and Shawky 2011). Thus, mycorrhizal plants possess enhanced activity of several antioxidant enzymes.

5.2.4 Abscisic Acid Content

Abscisic acid (ABA) is a phytohormone well known for its signalling role in the regulation of plant growth and development and also plays an important role in the response of the plant to abiotic stress, including salinity stress. ABA promotes stomatal closure to reduce water loss and induces the expression of stress-related genes, diminishing the damage it has caused (Evelin et al. 2009). It has been documented that mycorrhization can alter the ABA levels in the host plant (Duan et al. 1996; Estrada-Luna and Davies 2003). The effects of AMF species on ABA content also varied with the host plants (Evelin et al. 2009).

5.3 Physiological Changes

Salt stress can affect several physiological mechanisms in the plant such as photosynthetic efficiency, membrane disruption, gas exchange and induce physiological drought by altering water status. Various investigations demonstrated that AMF symbiosis can alleviate such effects by employing various mechanisms which are discussed below.

A higher chlorophyll content in leaves of mycorrhizal plants under saline conditions has been observed by various authors (Colla et al. 2008; Selvakumar and Thamizhiniyan 2011). This suggests that salt interferes less with chlorophyll synthesis in mycorrhizal than in non-mycorrhizal plants (Giri and Mukerji 2004). The antagonistic effect of Na^{2+} on Mg^{2+} uptake is counterbalanced and suppressed in the presence of mycorrhiza, thereby increase chlorophyll synthesis (Giri et al. 2003).

AMF-colonized plants exhibited higher chlorophyll fluorescence which is a measure of photosynthetic efficiency of photosystem II, as well as an enhanced stomatal conductance rate both under non-saline and under saline conditions. These two positive effects may also have accounted for the enhanced plant growth of AMF-colonized plants, most probably by enhancing CO_2 fixation under salt stress. In this sense, several studies have shown a correlation between tolerance to abiotic stresses and maintenance of efficiency of photosystem II, which also sustained plant productivity (Loggini et al. 1999; Ruiz-Sánchez et al. 2010; Aroca et al. 2013). The higher values of photosynthetic efficiency in mycorrhizal plants indicate that the photosynthetic apparatus of these plants is less damaged by the salt stress imposed (Germ et al. 2005; Redondo-Gómez et al. 2010). Mycorrhiza-inoculated plants also showed higher non-photochemical quenching than the uninoculated plants which protect the leaf from light-induced damage (Maxwell and Johnson 2000; Sheng et al. 2008). The higher performance of photosystem II and the enhanced stomatal conductance in mycorrhizal plants could have contributed to decreased photorespiration, leading to a lower production of reactive oxygen species in these plants (Cadenas 1989; Ruiz-Sánchez et al. 2010), thus contributing to an enhanced salinity tolerance and growth.

Some studies have shown that colonization of plant roots by the AM fungus *G. intraradices* prevented leaf dehydration caused by salinity (Aroca et al. 2006; Porcel et al. 2006). Lower water saturation deficit and higher turgor potential in AMF plants also improve the water status of the plant (Al-Garni 2006; Sheng et al. 2008). AMF colonization induces an increase in root hydraulic conductivity of the host plants under osmotic stress conditions (Sánchez-Blanco et al. 2004; Aroca et al. 2007). AMF-colonized plants are able to fix more CO_2 than non-inoculated plants and hence their growth is improved (Querejeta et al. 2007).

AMF-inoculated plants maintain a higher electrolyte concentration than that of non-mycorrhizal plants by maintaining membrane integrity and stability (Garg and Manchanda 2008; Kaya et al. 2009). Consequently, higher electrical conductivity of mycorrhizal roots was observed than the non-mycorrhizal roots (Garg and Manchanda 2008). This suggests that mycorrhizal plants had a much lower root plasma membrane electrolyte permeability than the non-mycorrhizal plants. The increased membrane stability has been attributed to mycorrhiza-mediated enhanced P uptake and increased antioxidant production (Feng et al. 2002).

5.4 Molecular Changes

A few studies are available on molecular mechanism of AMF symbiosis to alleviate salinity stress in plants. The expression studies and/or overexpression of a few proteins, including cation channels and transporters, Δ1-pyrroline-5-carboxylate synthetase (P5CS), late embryogenesis abundant protein (Lea), ABA and aquaporins, is documented in AMF symbiosis during salinity.

5.4.1 Aquaporins

Aquaporins belong to the major intrinsic protein (MIP) family of transmembrane channels that facilitate and regulate the passive movement of water molecules but not of H^+ and other ions following a water potential gradient (Hill et al. 2004; Kruse et al. 2006). In plants, aquaporins are subdivided into five evolutionarily distinct subfamilies: the plasma membrane intrinsic proteins (PIPs), the tonoplast intrinsic proteins (TIPs), the small basic intrinsic proteins (SIPs), the nodulin-like intrinsic proteins (NIPs) (Chaumont et al. 2001; Johanson et al. 2001) and the uncharacterized X intrinsic proteins (XIPs) (Gupta and Sankararamakrishnan 2009), which have been shown recently to transport a variety of uncharged substrates (Bienert et al. 2011). The role of aquaporins in water uptake was confirmed by inhibition of root water transport by the general aquaporin blocker mercury ions (Maggio and Joly 1995).

Expression analysis of aquaporin genes in salt-stressed AMF plants revealed contrasting results. A significantly downregulated expression of LeTIP and LePIP1 was observed in non-treated controls and salt-stressed roots of *Lycopersicon esculentum*, but LePIP2 transcripts level did not alter. Moreover, the expression of aquaporin was drastically reduced after AMF colonization than salinity (Ouziad et al. 2006). In contrary to these results, a higher expression of all PvPIP genes is observed in AMF *Phaseolus vulgaris* roots than non-AMF plants (Aroca et al. 2007). Similarly, Jahromi et al. (2008) reported that under salt-stress conditions (0–100 mM NaCl), mycorrhizal *Lactuca sativa* plants maintained the expression of the LsPIP2 gene and upregulation of LsPIP1 gene, while in the absence of salinity, the expression of lettuce PIP1 and PIP2 genes was inhibited by mycorrhization. Thus, under salinity, AMF symbiosis enhanced the expression of PIP genes, and its protein could contribute to regulating root water permeability to better tolerate the osmotic stress generated by salinity (Aroca et al. 2007; Jahromi et al. 2008). These results point to the possibility that AMF differentially exert control on the expression of different members of the large family of aquaporins (Ouziad et al. 2006) and that each PIP gene analysed may have a different function and regulation in AMF symbiosis. How much this contrasting result reflects biological or technical differences remains to be evaluated. Further analyses should focus on those aquaporins with a proven capacity for water transport such as PIPs (mainly the PIP2 subgroup) and TIPs. These analyses should be correlated with measures of root and leaf hydraulic conductivities and water status in order to determine the final influence of the regulated aquaporins on the tissue water permeability and content.

5.4.2 Δ1-Pyrroline-5-carboxylate Synthetase, Late Embryogenesis Abundant Protein and ABA

The expression of genes encoding Δ1-pyrroline5-carboxylate synthetase (LsP5CS), late embryogenesis abundant protein (LsLea) and ABA (Lsnced) was determined following varied salt treatments (0–100 mM NaCl) on *L. sativa* plants colonized by

Glomus intraradices (Jahromi et al. 2008). The PC5S enzyme catalyses the rate-limiting step in the biosynthesis of proline. Late embryogenesis abundant proteins act as stress markers. They also possess chaperone-like activity, thus having a protective role during osmotic stress. Lsnced encodes for 9-cis-epoxycarotenoid dioxygenase, a key enzyme in the biosynthesis of the stress hormone ABA. ABA promotes stomatal closure to minimize transpirational water loss. It also mitigates stress damage through the activation of many stress-responsive genes, which collectively increases plant-stress tolerance (Bray 2002). They reported a higher expression of genes LsP5CS and Lsnced in non-AMF plants than AMF plants at 50 mM NaCl, though at 100 mM, the levels were similar. The LsLea gene was found to express under conditions of salt stress, and the induction of this gene was found to be lower in AMF plants than non-AMF plants. The lower expression of these genes under AMF symbiosis suggests that AMF plants were less strained than non-AMF plants by salinity stress imposed, which may be due to a primary salt avoidance mechanism such as Na^+ and Cl^+ accumulation (Giri et al. 2003; Al-Karaki 2006).

5.4.3 Cation Channels and Transporters

Ouziad et al. (2006) analysed the expression of two antiporters (LeNHX1 and LeNHX2) in tomato-AM symbiosis during salinity stress. They reported that AMF symbiosis did not alter the expression of these genes under salinity. Zhongqun and Huang (2013) reported that mycorrhizal colonization significantly reduced the amount of LeNHX1transcript under salt stress. These results could not clear the mechanism of LeNHX1 and LeNHX2 genes in tomato-AM symbiosis during salinity stress. Under salinity conditions Na^+ can be exported either into the apoplast by a plasma membrane-associated Na^+/H^+ antiporter or into vacuoles by a tonoplast-associated Na^+/H^+ antiporter (Blumwald et al. 2000). In tomato, there are at least four LeNHX-type genes. LeNHX1, 3 and 4 are tonoplast Na^+/H^+ antiporter (Pardo et al. 2006) and LeNHX2 has been shown to be a K^+/H^+ transporter (Venema et al. 2003). Thus study of all genes during salinity and AM symbiosis is required to know the role of LeNHX genes in salt tolerance.

The cyclic nucleotide-gated ion channel (CNGC) family is composed of non-selective cation channels that enable the uptake of Na^+, K^+ and Ca^{2+} (Kaplan et al. 2007). It has been suggested that CNGCs contribute to sodium reallocation within the plant tissues, assisting the plant in coping with salinity stress (Porcel et al. 2012).

Kugler et al. (2009) have reported that both AtCNGC19 and AtCNGC20 were upregulated in the shoot of *Arabidopsis* in response to elevated NaCl. While in the root, CNGC19 did not respond to changes in the salt concentration, in the shoot, it was strongly upregulated. To demonstrate the function of CNGCs in tomato under salt stress, the SlCNGC virus-induced gene-silenced tomato plants were examined for their role in salt tolerance. SlCNGC6-silenced plants exhibited more severe symptoms than that of SlCNGC1-, SlCNGC7-, SlCNGC8-, SlCNGC11- and SlCNGC14-silenced plants under salinity. At 3 days after 0.4 M NaCl supply, SlCNGC6-silenced plants completely wilted with all leaves desiccated. Moreover, the RWC in SlCNGC6-silenced plant leaves (49.4) was significantly lower than in control (58.3 %). This RWC data correlated well with the severity of wilting symptoms in the silenced plants. These results demonstrated that SlCNGC6-silenced plants are more sensitive, while SlCNGC1-, SlCNGC8- and SlCNGC14-silenced plants are more tolerant to high concentration of salt stress, and indicated that SlCNGC6 may play a positive role, while SlCNGC1, SlCNGC8 and SlCNGC14 may play a negative role in salt tolerance in tomato (Saand et al. 2015). These results imply that different CNGC genes may play a role in salt stress.

There are several studies showing that AMF plants have better K^+:Na^+ ratios than non-AMF plants. However, the molecular mechanisms involved in such an effect are almost completely unknown. Thus, studying the possible regulation of genes encoding known ion transporters, such as high-affinity K^+ transporter (HKT), potassium channel (AKT), salt overly sensitive (SOS) and Na^+/H^+ exchanger (NHX), and probably also CNGCs, during the response of AMF symbiosis to salinity is a promising field. These studies should be accomplished in combination with measurements of sodium and potassium content and their ratios in the different plant tissues. Together, this should allow a better understanding of whether AMF symbiosis affects Na^+ and K^+ uptake, distribution and compartmentation within the plant cell and should shed further light on new mechanisms involved in the enhanced tolerance of AMF plants to salt stress.

5.5 *Enhanced Nutrient Uptake*

Facilitating the nutrient uptake for plants by the use of mycorrhiza has repeatedly been highlighted by the researchers throughout the world. Apart from primary soil nutrients (N, P, K), AMF proved its efficiency to absorb Mg, Ca, Cu, Zn, Fe, Ni and Cd through plant roots. It is often been considered that uptake and transport of nutrients from soil is the primary function of mycorrhizal fungi associated with plant roots (reviewed in Quilambo 2003).

Phosphorus absorption has often been easier under mycorrhizal inoculation; even under saline soil, the P uptake was found higher (Tian et al. 2004; Sharifi et al. 2007; Al-Khaliel 2010). Phosphorus being a poorly mobile nutrient as PO_4^{-3}, when show a positive influence in the presence of AMF towards absorption in plant roots, and that also under problem (saline) soil, demands a special mention. Despite P, N and K uptake was also found to improve by association of AMF (Rabie and Almadini 2005; Al-Khaliel 2010). Garg and Manchanda (2008) and Giri and Mukerji (2004) reported a higher N uptake under soil salinity by *Cajanus cajan* and *Sesbania* sp., respectively, in the presence of *Glomus* spp. Enhancement of potassium uptake under salt-stressed soil was also found for soybean plants (Sharifi et al. 2007).

A selective uptake of nutrients is also sometimes mentioned by AMF. Balancing the K^+/Na^+ ratio in plant tissues is a major concern to avoid the deleterious effects of soil salinity. AMF was also found to interfere in the increased uptake of K with concomitant decreased uptake of Na by plant roots (Zuccarini and Okurowska 2008).

Ca^{+2} and Mg^{+2} were also found to be absorbed more by plant roots with myccorrhizal association despite of soil salinity (Yano-Melo et al. 2003; Sharifi et al. 2007; Giri and Mukerji 2004).

This sort of beneficial activities by AMF often enhances the nutrient use efficiency of plants in marginal or degraded soils depleted in essential nutrients. This may further aggravate the fertility and productivity of these soils.

6 Conclusions

AMF have the potential to ameliorate salt stress and improve plant growth. AMF-mediated amelioration is attributed due to accumulation of different solutes and higher uptake of water and nutrients under salinity conditions. AMF symbiosis also regulates various plant physiological and biochemical processes such as water potential, ionic balance, stomata conductance, maintenance of photosynthesis, reduction of oxidative damage through antioxidant production and hormone-mediated signal transduction. However, the ultimate mechanisms that allow AMF plants a higher tolerance to salinity are still in infancy. Molecular bases of regulation of ionic homeostatis, cation to proton antiporter and cyclic nucleotide-gated channels under AMF symbiosis are largely unknown. Thus investigation on these aspects on arbuscular mycorrhizal symbiosis under salinity is a promising field that should shed further light on new mechanisms involved in the enhanced tolerance of AM plants to salt stress. Further, transcriptomic analysis of some AMF is a promising tool that could provide new data regarding fungal genes that may also participate in the response of AMF symbiosis to salinity stress.

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Ecology of Saline Soil Microorganisms

Ratna Trivedi

1 Introduction

Soil salinity is a key problem severely affecting the agricultural productivity mainly of the coastal areas and semiarid regions. High salt concentration is known to cause stress and damage to the plant starting from the germination phase through developmental stages and harvesting time. Salt prevents limits or disturbs the normal metabolism, water quality and nutrient uptake of plants and soil biota. There has been a constant effort to improve the soil fertility and productivity of saline soil through application of biofertilizers.

The use of soil and irrigation water with a high content of soluble salts is a major limiting factor for crop productivity in the semiarid areas of the world. Whilst important physiological insights about the mechanisms of salt tolerance in plants have been gained, the transfer of such knowledge into crop improvement has been limited. The identification and exploitation of soil microorganisms (especially rhizosphere bacteria and mycorrhizal fungi) that interact with plants by alleviating stress opens new alternatives for a pyramiding strategy against salinity, as well as new approaches to discover new mechanisms involved in stress tolerance. Although these mechanisms are not always well understood, beneficial physiological effects include improved nutrient and water uptake, growth promotion and alteration of plant hormonal status and metabolism. This review aims to evaluate the beneficial effects of soil biota on the plant response to saline stress, with special reference to phytohormonal signalling mechanisms that interact with key physiological processes to improve plant tolerance to the osmotic and toxic components of salinity.

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Improved plant nutrition is a quite general beneficial effect and may contribute to the maintenance of homeostasis of toxic ions under saline stress. Furthermore, alteration of crop hormonal status to decrease evolution of the growth retarding and senescence-inducing hormone ethylene (or its precursor 1-aminocyclopropane-1-carboxylic acid) or to maintain source–sink relations, photosynthesis and biomass production and allocation (by altering indole-3-acetic acid and cytokinin biosynthesis) seem to be promising target processes for soil biota-improved crop salt tolerance.

2 Halotolerant Microbial Species

Towards this effort, many halotolerant microbial species have been isolated and identified which include *Azotobacter*, *Azospirillum*, phosphobacteria and blue-green algae from marine aquatic sediments. The bacterial sequences were assigned into 5784 operational taxonomic units (OTUs, based on ≥97 % sequence identity), representing 24 known bacterial phyla, with *Proteobacteria* (44.9 %), *Actinobacteria* (12.3 %), *Firmicutes* (10.4 %), *Acidobacteria* (9.0 %), *Bacteroidetes* (6.8 %) and *Chloroflexi* (5.9 %) being predominant. *Lysobacter* (12.8 %) was the dominant bacterial genus in saline soils, followed by *Sphingomonas* (4.5 %), *Halomonas* (2.5 %) and *Gemmatimonas* (2.5 %). Archaeal sequences were assigned to 602 OTUs, primarily from the phyla Euryarchaeota (88.7 %) and Crenarchaeota (11.3 %). Halorubrum and *Thermofilum* were the dominant archaeal genera in saline soils. Rarefaction analysis indicated less than 25 % of bacterial diversity and approximately 50 % of archaeal diversity in saline soil (Fig. 1).

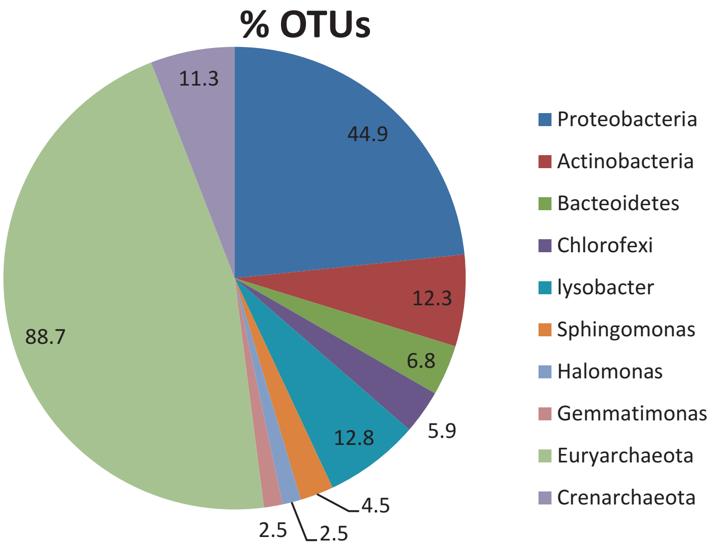

Fig. 1 Percent OTUs of microbial diversity in saline soils

Soil salinity is a major problem facing the agricultural production in many fields and soil infertility in the treatment or the regions due to the presence of high concentrations of salt. Most leguminous plants have a neutral ground or are slightly acid for growth, particularly when they depend on the symbiotic fixation of N_2, and therefore more sensitive to salinity than their counterparts *Rhizobium*, and therefore symbiosis is more sensitive to salt stress than free-living rhizobia. The methods used in recent years to reduce the effects of stress on production of pulses and salt focused on the selection of the host genotypes that are tolerant to a lot of salt. *Rhizobium* spp. can support up to 500 mM NaCl which discovered a leg for certain types of Rhizobia adapted to saline conditions by the intracellular accumulation of low-molecular-weight organic solutes called osmolytes, Zoals glutamate, trehalose, glycine betaine and multi-amine or the accumulation of K^+.

Nitrogen-fixing legumes tolerant to salinity represent an important alternative to improve fertility. Saline soil has an excess of soluble salt in the soil solution, the liquid located between aggregates of soil. A sodic soil has too much sodium associated with the negatively charged clay particles. Salinity occurs through natural or human-induced processes that result in the accumulation of dissolved salts in the soil water to an extent that inhibits plant growth. Natural salinity results from the accumulation of salts over a long period of time and is caused by two natural processes. The first is the weathering process that breaks down rock and releases soluble salts of various types, mainly chloride of sodium, calcium and magnesium and to a lesser extent, sulphates and carbonates. Sodium chloride is the most soluble salt. The second is the deposition of oceanic salt carried in wind and rain. Human-induced salinity results from human activity that change the hydrologic balance of the soil between water applied (irrigation or rainfall) and water used by crops (transpiration). The most common causes are (1) land clearing and the replacement of perennial vegetation with annual crops and (2) irrigation schemes using salt-rich irrigation water or having insufficient drainage.

Water deficit and salinity disrupt photosynthesis and increase photorespiration, altering the normal homeostasis of cells and cause an increased production of reactive oxygen species (ROS) such as the super oxide radical, hydrogen peroxide and hydroxyl radical (Miller et al. 2010). Under optimal growth conditions, ROS are mainly produced at low level in organelles such as chloroplasts, mitochondria and peroxisome. The enhanced production of ROS during stress can pose a threat to cells, but it is thought that ROS also act as signals for the activation of stress response and defence pathways.

3 PGPR in Stress

Plants in their natural environment are colonized both by endocellular and intracellular microorganisms. Rhizosphere microorganisms, particularly beneficial bacteria and fungi, can improve plant performance under stress environments and, consequently, enhance yield both directly and indirectly. Some plant growth-promoting rhizobacteria (PGPR) may exert a direct stimulation on plant growth and development by providing plants with fixed nitrogen, phytohormones, iron that has been sequestered by bacterial siderophores, and soluble phosphate. Others do this indirectly by protecting the plant against soilborne diseases, most of which are caused by pathogenic fungi. Common adaptation mechanisms of plants exposed to environmental stresses, such as temperature extremes, high salinity, drought and nutrient deficiency, or heavy metal toxicity, include changes in root morphology, a process in which phytohormones are known to play a key role. The majority of root-associated bacteria that display beneficial effects on plant growth produce indole-3-acetic acid (IAA). Inoculation of various plant species with such bacteria leads to increased root growth and/or enhanced formation of lateral roots and root hairs that can result in enhanced tolerance to abiotic stress. Bacterial IAA production also stimulates the activity of the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase involved in the degradation of the ethylene precursor ACC. ACC deaminase activity could be helpful in sustaining plant growth and development under stress conditions by reducing stress-induced ethylene production. Modulation of other major plant hormones could improve crop salt tolerance by reducing the toxic effects of salinity. A number of nitrogen-containing compounds accumulate in plants exposed to saline stress. The accumulation of the amino acid proline is one of the most frequently reported modifications induced by water and salt stress as well as other stresses in plants. It has been found that Medicago plants infected by IAA-overproducing PGPR strains are able to overcome different stressful environmental conditions and accumulate high levels of proline. The increased expression levels of two genes involved in the first two steps of proline biosynthesis from glutamic acid confirmed these results.

Plants with high levels of antioxidants, either constitutive or induced, have been reported to have greater resistance to this oxidative damage. The activities of the antioxidative enzymes such as catalase (CAT), ascorbate peroxidase (APX), guaiacol peroxidase (POX), glutathione reductase (GR) and superoxide dismutase (SOD) increase under salt stress in plants and a correlation between these enzyme levels and salt tolerance. It has been found that Medicago plants infected with IAA-overproducing PGPR strains showed high antioxidant enzymes activity which contributed to enhance plant protection against salt stress. Considering the positive effects of PGPR strains on different plant cultivars and lines grown under salt stress conditions, we propose that such bacteria might be tested in field trial offering an economical and simple treatment to salt-sensitive plants.

4 Alleviating Salt Stress

A fruitful strategy to alleviate negative effects of salt stress in plants might be the co-inoculation of seeds with different PGPR species, such as *Rhizobium* and *Azospirillum*. Indeed, dual inoculation with *Rhizobium* and *Azospirillum* and other plant growth-promoting rhizobacteria was shown to increase the total nodule number of several legumes, acetylene reduction activities and the total N content of mineral macro- and micronutrients as compared to inoculation with *Rhizobium* alone. The presence of *Azospirillum* in the rhizosphere was reported to elicit or activate the hydrolysis of conjugated phytohormones and flavonoids in the root tissue, thus bringing about the release of compounds in their active forms.

4.1 Soil Bacteria

Populations of microorganisms live in close contact with the plant root zone called rhizosphere. Here the number of microorganisms is usually higher than in other soil areas. Thus, the plant root is thought to be a major source of nutrients for microorganisms living in the rhizosphere. Indeed, plants supply organic carbon to their surroundings in the form of root exudates, and rhizobacteria respond to this exudation by means of chemotaxis towards the exudate source modulating their metabolism to optimize nutrient acquisition (Trivedi and Arora 2013). Soil bacteria beneficial to plant growth are usually referred to as plant growth-promoting rhizobacteria (PGPR), capable of promoting plant growth by colonizing the plant root. Bacteria of diverse genera such as *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Enterobacter*, *Pseudomonas* and *Serratia* (Gray and Smith 2005), as well as *Streptomyces* spp. (Dimkpa et al. 2008, 2009; Tokala et al. 2002) were identified as PGPR. According to their residing sites, PGPR can be divided in iPGPR, which live inside the plant cells and are localized in specialized structures, the so-called nodules, and ePGPR which live outside the plant cells and do not produce organs like nodules but still prompt plant growth. Although the exact mechanisms of plant growth stimulation remain largely speculative, possible explanation includes (1) production of hormones like abscisic acid, gibberellic acid, cytokinins and auxin, i.e. IAA; (2) production of essential enzymes, 1-aminocyclopropane-1-carboxylate (ACC) deaminase to reduce the level of ethylene in the root of developing plants; (3) nitrogen fixation; (4) production of siderophores; (5) solubilization and mineralization of nutrients, particularly mineral phosphate; and (6) improvement of abiotic stresses resistance.

4.2 Mechanisms for Stress Conditions

Various stress conditions viz., dehydration, salinity, low-and high-temperature stresses and other stresses lead to metabolic toxicity, membrane disorganization, generation of ROS, inhibition of photosynthesis, reduced and altered nutrient acquisition (Fig. 2).

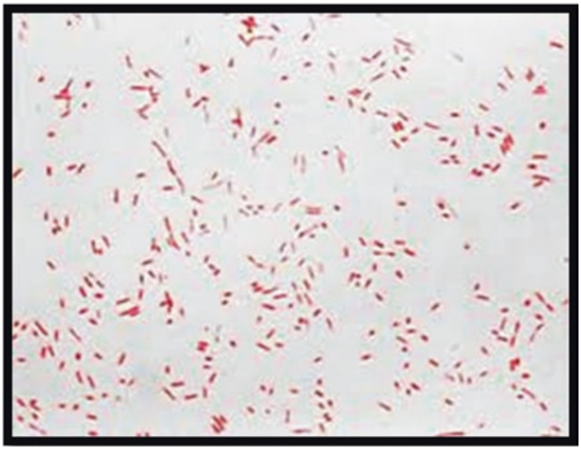

Fig. 2 Gram negative rhizobia hormone levels. Accumulation of osmoprotectants, production of superoxide radical scavenging mechanisms, exclusion or compartmentation of ions by efficient transporter and symporter systems and production of specific enzymes involved in the regulation of plant hormones are some of the mechanisms that plants have evolved for adaptation to abiotic stresses

4.2.1 Phytohormones Synthesis and Modulation

Plants are sessile organisms with a high level of physiological plasticity, enabling survival under a wide variety of environmental insults. This is due to the continuously active shoot and root meristems and their capability to generate new organs after embryogenesis (Wolter and Jurgens 2009). They have developed an extensive array of defensive responses that includes changes in the root morphology. The root architecture of the plants, which is determined by the pattern of root branching (lateral root formation) and by the rate and direction of growth of individual roots (Malamy 2005), constitutes an important model to study how developmental plasticity is translated into growth responses under several environmental stresses. Morphogenesis is tightly linked to hormonal homeostasis, with several hormones controlling cell elongation, cell division and reorientation of growth.

According to Spaepen, plant tissues that showed the presence of bacteria, an increased number of IAA-producing PGPR strains detected inside the plant tissues. Various plant species inoculated with such bacteria showed increased root growth and/or enhanced formation of lateral roots and roots hairs. For example, the stimulatory effect of *Azospirillum* strains on the development of roots is well documented. Morphological plant root changes have been observed repeatedly upon *Azospirillum* inoculation and have been attributed to the production of plant growth-promoting substances: auxins, cytokinins and gibberellins, with auxin production being quantitatively the most important. Specific evidences for the involvement of auxins produced by *Azospirillum* in roots proliferation were obtained in many cases. Addition of filter-sterilized culture supernatants of *Azospirillum brasiliense* to rice roots grown in hydroponic tanks increased root elongation, root surface area, root dry matter and development of lateral roots and root hairs, compared with untreated roots. Similarly, a cell-free supernatant of *A. brasiliense* Cd applied to soybean plants induced many roots and increased root length. Exogenous application of IAA to bean roots resembled responses of these plants to inoculation with *Azospirillum*. More direct evidence for the importance of IAA was provided when several IAA-attenuate mutants were compared with their parental wild types for their effect on plant growth. A mutant of A. brasiliense with low production of phytohormones, but high N_2-fixing activity, did not enhance root growth over uninoculated controls. Considering the relationship between IAA and ethylene precursor ACC, the positive effects of IAA on root growth can be either direct or indirect through the reduction of ethylene levels.

Pseudomonas fluorescens strain containing ACC deaminase activity enhanced the saline resistance in groundnut plants and increased yield as compared to plants inoculated with *Pseudomonas* strains lacking ACC deaminase activity. *Pseudomonas putida*, which produces IAA and ACC deaminase, protected canola seedling from growth inhibition by high levels of salt. Siddikee et al. (2010) have also confirmed that inoculation with 14 halotolerant bacterial strains ameliorate salt stress in canola plants through the reduction of ethylene production via ACC deaminase activity. Inoculation of maize plants with *Pseudomonas fluorescens* containing ACC deaminase boosted root elongation and fresh weight significantly under saline conditions (Kausar and Shahzad 2006). Inoculation with *Pseudomonas* spp. containing ACC deaminase partially eliminates the effects of drought stress on growth, yield and ripening of pea (*Pisum sativum L.*) (Arshad et al. 2008). Nadeem et al. (2010) reported that rhizobacteria capable of producing ACC deaminase mitigate salt stress in wheat.

4.2.2 The Effect of Salinity on the Soil Microorganisms

The microbial communities of the soil perform a fundamental role in cycling nutrients, in the volume of organic matter in the soil and in maintaining plant productivity. Thus, it is important to understand the microbial response to environmental stress, such as high concentrations of heavy metals of salts, fire and the water content of the soil. Stress can be detrimental for sensitive microorganisms and decrease the activity of surviving cells, due to the metabolic load imposed by the need for stress tolerance mechanisms. In a dry hot climate, the low humidity and soil salinity are the most stressful factors for the soil microbial flora and frequently occur simultaneously.

Saline stress can gain importance, especially in agricultural soils where the high salinity may be a result of irrigation practices and the application of chemical fertilizers. Research has been carried out on naturally saline soils and the detrimental influence of salinity on the microbial soil communities and their activities reported in the majority of studies. The effect is always more pronounced in the rhizosphere according to the increase in water absorption by the plants due to transpiration. The simple explanation for this is that life in high salt concentrations has a high bioenergetic taxation, since the microorganisms need to maintain osmotic equilibrium between the cytoplasm and the surrounding medium, excluding sodium ions from inside the cell. As a result, energy sufficient for osmo-adaptation is required.

4.3 Fungi

The composition of the microbial community may be affected by salinity since the microbial genotypes differ in their tolerance of a low osmotic. In fungi, a low osmotic potential decreases spore germination and the growth of hyphae and changes the morphology and gene expression, resulting in the formation of spores with thick walls. Fungi have been reported to be more sensitive to osmotic stress than bacteria. There is a significant reduction in the total fungal count in soils salinized with different concentrations of sodium chloride. Similarly, with an increase in the salinity level to above 5 %, the total count of bacteria and actinobacteria was drastically reduced. Van Bruggen and Semenov (2000) reported that on a long-term basis there is a decrease in the genetic diversity of fungi as a result of stress. On the other hand, Killham (1994) mentioned that the filamentous fungi are highly tolerant of hydric stress. However they have to deal with the increase in osmotic pressure and may therefore change their physiology (Killham 1994) and morphology in response to this (Fig. 3).

Two strategies used by microorganisms to adapt to osmotic stress were described by Killham (1994), both of which result in an accumulation of solutes in the cell to counteract the increase in osmotic pressure. One is the selective exclusion of the solute incorporated (e.g. Na^+, Cl^-), thus accumulating the ions necessary for metabolism (e.g. NH_4^+). The other cell adaptation mechanism is the production of organic compounds that will antagonize the concentration gradient between the soil solution and the cell cytoplasm. This adaptation finally results in a physiologically more active microbial community and, in consequence, reduced substrate use efficiency.

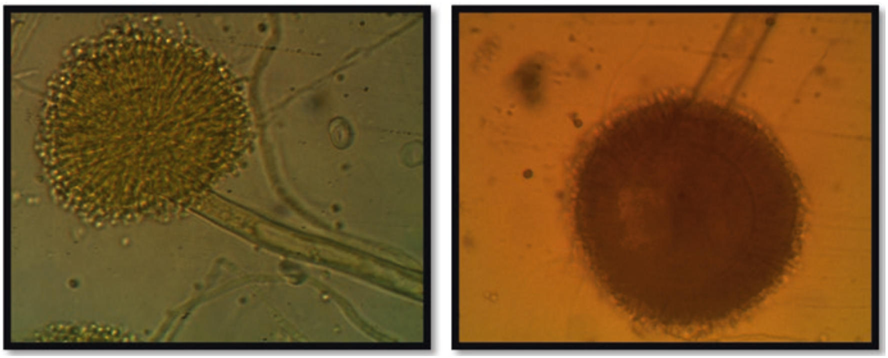

Fig. 3 Fungi grow on saline soil

However these mechanisms are known for single microorganisms, but little has been studied at the community level. According to Oren (2001) and Hagemann (2011), whilst sensitive cells are damaged by the low osmotic potential, some microorganisms can adapt by accumulating osmolytes (including amino acids in bacteria and polyols in fungi) that help retain water (Beales 2004). Nevertheless, the synthesis of osmolytes requires large amounts of energy, 30–110 ATPs, when compared to the 30 ATPs required to synthesize the cell wall (Oren 1999), representing a significant metabolic responsibility for the microorganisms, and reduces the energy available for growth.

In order to better understand what happens to the microbial biomass and its activity in saline soils, one must also consider the water potential (osmotic potential + matrix potential), especially the low water content when the salt concentration in the soil solution increases. Since the water content changes, the microorganisms will be subject to different osmotic and water potentials, even though the modifications in the electrical conductivity (EC) measurement are small. Thus the EC is an indicator of little importance with respect to microbial stress in saline environments. According to Chowdhury et al. (2011), microorganisms have two strategies to respond to the water potential. A decrease in this potential to up to −2 MPa damages a proportion of the microbial population, but the remaining microorganisms will adapt themselves and be active. For lower water potentials, the adaption mechanisms are not sufficient, and, although the microorganisms survive, they do so with reduced activity per unit of biomass. However, more studies are required in different soils and, in particular, in saline soils, in order to discern which effects can be generalized. Since the greater part of soil biochemical transformations are dependent on or related to the presence of enzymes, an evaluation of their activities could be useful to indicate if a soil is adequately carrying out the processes closely connected to its quality.

5 Salinity Influencing Microbial Enzyme Activity

Soil enzymes carry out a fundamental role in the ecosystems, acting as catalysts of various reactions that result in the decomposition of organic residues, cycling of nutrients and the formation of organic matter in the soil, in addition to taking part in intercellular metabolic reactions responsible for the functioning and maintenance of living beings, quite apart from their biotechnological potential, with various applications in the industrial and environmental areas. They generally originate from microorganisms but can also have animal and vegetable origins.

Amongst the diverse soil enzymes, dehydrogenase, β-glucosidase, urease and phosphatases are important in the transformation of different nutrients for plants. The activity of dehydrogenase reflects the total oxidative capacity of the microbial biomass (Nannipieri et al., 1990) and is involved in the central aspect of metabolism. β-glucosidase is an important enzyme in the land carbon cycle, in the production of glucose, which constitutes an important energy source for the microbial mass. Thus, the determination of β-glucosidase activity, amongst other hydrolytic enzyme activities, has been suggested as a good indicator of soil quality. The phosphatases play an important role in the transformation of organic phosphorus into inorganic forms more appropriate for plants. Phosphorus (P) is one of the essential nutrients for a plant, and the greater part of soil phosphorus occurs in the organic form. Urease predominates amongst the enzymes involved in the N cycle of the soil. It catalyses the hydrolysis of urea into ammonia or the ammonium ion, depending on the pH of the soil and carbon dioxide. Urease and catalase are the enzymes responsible for the decomposition of vegetable residues. The activity of these enzymes transforms the residue into humus, which is then completely decomposed into the free nutrients. On the other hand, amylase hydrolyzes the polysaccharides, converting them into simpler constituents. The activity of this enzyme is associated with high productivity of the crops.

Under laboratory conditions, salinity influenced soil enzyme activity negatively, although the degree of inhibition varied according to the enzyme analysed and the nature and amount of soil added. Dehydrogenase activity was severely inhibited, whereas the hydrolases showed a milder degree of inhibition. The reduction of enzyme activity in saline soils could be due to the osmotic dehydration of the microbial cells that liberate intracellular enzymes, which become vulnerable to the attack by soil proteases, with a consequent decrease in enzyme activity. The salting-out effect modifies the ionic conformation of the protein-enzyme active site, and specific ionic toxicity causes a nutritional imbalance for microbial growth and subsequent enzyme synthesis. Ahmad and Khan (1988) and Rietz and Haynes (2003) obtained similar results. According to Rietz and Haynes (2003), the increase in salinity due to an influx of salty water under controlled conditions decreased the carbon content of the soil microbial biomass and enzymes. Other researchers also indicated the effects of soil salinity on the carbon of microbial biomass and on enzyme activity. It also showed that an increase in soil salinity inhibited the enzyme activities of benzoyl argininamide alkaline phosphatase and β-glucosidase and also microbial respiration. Invertase and urease activities were also severely reduced by an increasing concentration of sodium chloride (NaCl) during incubation. In addition, the effect was inhibitory of nitrate reductase in the majority of the treatments. On comparing the enzyme activities of saline soil with those of normal soil, it also observed a decline in amylase, catalase, phosphatase and urease activities with increasing salinity.

Controlled conditions (laboratory) do not usually reflect the natural situation prevailing in coastal region soils, where the salinity varies temporally. Tripathi et al. (2006, 2007) studied the influence of the salinity of arable soils in Indian coastal regions on the microbial biomass and the following enzyme activities: dehydrogenase, β-glucosidase, urease, and acid and alkaline phosphatases, in three different seasons of the year. The microbial and biochemical parameters were adversely affected by the salinity, and the most extreme situation occurred in the summer. Of the enzymes studied, the activity of dehydrogenase was the most affected. In coastal ecosystem or the mangrove swamps, areas restricted to zones between coastal seas and islands in tropical regions, associated with estuaries, bays and lagoons in places, are protected from the impact of waves, where the salinity is between 5 and 30 % but can reach 90 % (Museu do Una 2010). This is a highly degraded natural environment for a variety of reasons, amongst which is the discharge of domestic and industrial effluent. Variations in the salinity of this environment can affect the retention of the pollutants and the microbiological responses as a function of the discharge of effluent. On investigating such areas, Tam (1998) observed that the addition of effluent to mangrove swamps, independent of their salinity, stimulated microbial growth and increased the activities of the enzymes dehydrogenase and alkaline phosphatase. According to the author, these effects were due to supplementation with additional carbon sources and other nutrients provided by the effluent.

Considering the forecast for an increase in saline and sodic areas, an understanding of the effects of salinity and sodicity on the soil carbon (C) stock and flow is fundamental for environmental management. Wong et al. (2008) evaluated the effects of salinity and sodicity on the microbial biomass and on soil respiration, under controlled conditions, submitting perturbed soil samples to leaching after receiving different salt concentrations. The highest soil respiration rates were observed in soils with low salinity and the lowest in soils with medium salinity, whilst the microbial biomass was greater in the treatments with high salinity and lower in those with low salinity. According to the authors, the results can be attributed to a greater availability of substrate in high salt concentrations, or by an increase in the dispersion of the aggregates of soil or from the dissolution or hydrolysis of the organic material in the soil, which can compensate, at least in part, the stress to which the microbial population is submitted in high salt concentrations. The apparent disparity between the evolution of respiration and that of the biomass could be due to a change induced in the microbial population from one dominated by more active microorganisms to one dominated by less active microorganisms. The microbial biomass is an important labile fraction of the soil organic matter, functioning both as an agent of transformation and recycling of the organic matter and soil nutrients, as also of a source of nutrients for the plants. It is also a potential source of enzymes in the soil.

6 Soil Nutrient Transformation

High salinity reduces the microbial biomass, affects amino acid capture and protein synthesis and respiration and causes increases and decreases in C and N mineralization. Since the soil organic matter and, consequently, the biomass and microbial activity are generally more relevant in the first few centimetres at the surface of the soil, salinization close to the surface can significantly affect a series of microbiologically mediated processes. This is a considerable problem, since the microbial processes of the soil control its ecological functions and fertility. The availability of nutrients for plants is regulated by the rhizospheric microbial activity.

Thus any factor affecting this community and its functions influences the availability of nutrients and growth of the plants. One of the microbial responses playing a significant role in plant growth is the internal recycling of nitrogen (N) by way of immobilization and re-mineralization. In the majority of studies, the immobilization of NH_4^+-N is reported as being quicker than that of NO_3^--N, whilst the re-mineralization of the N immobilized in NH_4^+ is slower than that immobilized in NO_3^-. However, little has been reported about immobilization/re-mineralization in the two forms of N under conditions of salinity. Since nitrification is more or less inhibited in the presence of salts resulting in an accumulation of NH_4^+-N, the cycling of the two forms of N will have a significant impact on the dynamics and availability of N for the plants. According to Azam and Ifzal (2006), the presence of NaCl retards the N immobilization process. Both re-mineralization and nitrification were significantly retarded in the presence of NaCl, maximum inhibition occurring with 4000 mg NaCl kg^{-1} of soil. The inhibitory effect of NaCl on N re-mineralization was relatively higher in soils treated with NH_4^+. The results of this study suggest greater sensitivity to NaCl by microorganisms that have assimilated NO_3^-. However, N re-mineralization in the population that had assimilated NO_3^- was less affected by salinity when compared to the population that had assimilated NH_4^+.

In the latest years, saline soils received a great attention because of the general shortage of arable land, and of the increasing demand for ecological restoration of areas affected by secondary salinisation processes. This is due to the fact that naturally salt-affected soils have a biotechnological potential in their microbial communities, which represent not only a gene reserve for future exploitation in biotechnological applications, assuming they could be used in some kind of restoration or conservation techniques of saline environments, but they can also serve as model systems for exploring the relationships between diversity and activity at the soil level in selective/limiting situations. As outlined in the introduction, very few studies succeeded in addressing the beta diversity of the microbial species in soils, according to the different salt concentrations and, at a different scale, to bacterial taxa distribution in relation to salinity gradients.

Although some of the enumerated phyla related to saline soils have already been found by other authors, this study complements the limited information available on these extreme habitats by providing specific information on the type of distribution of different bacterial groups as a function of spatial gradients in salinity and pH. The analysis of bacterial 16S rRNA-based datasets obtained from a naturally saline soil revealed significant differences in bacterial community composition and diversity, along an increasing salinity level, which underlies a multi-scale spatial variability. What is more, a spatial heterogeneity of microbial communities at a relatively small scale has emerged from this study, especially with respect to the macroscale environmental scheme in terms of geography and soil. The soil of the study showed a patchy distribution of the vegetation structure and of chemical properties, which coincided with a heterogeneous distribution of many bacterial groups. Some bacterial phyla appeared, however, spread in the whole study area.

It is possible to make some assumptions that could be the basis for future in-depth studies on the association between groups of bacteria or on their variance in certain extreme environments. The first assumption is that spatial autocorrelation in terms of microbial diversity can hardly be found at the soil scales used for physical–chemical studies. According to some authors, spatial autocorrelation in soil ranges from 30 cm to more than 6 m, depending on the sampling extent considered. Some locations also found up to four different correlation length scales. The presence of nested scales of variability suggests that the environmental factors regulating the development of the communities in the saline soil of the present study may have operated at different scales. The presence of spatial patterns in the distribution of bacteria was demonstrated at the microscale which showed ranges of spatial autocorrelation of 1 mm and below. The second assumption is that an environment in which some limiting factors favour some microbial groups and not others is in fact compared to a set of islands that allow the formation of different communities, separated from each other by the discontinuity of the chemical–physical factors and by the availability of nutrients. One could imagine that in spite of the same element of "noise" (salinity), the spatial discontinuity allows the formation of more possible microbial assortments. Therefore, a patchy saline environment can contain not just a single microbial community selected to withstand extreme osmotic phenomena but many different though efficient communities. The occurrence of a significant number of "salinity unrelated" phyla (e.g. *Nitrospira*, *Spirochaetes*) captures our interest; therefore, we strongly believe that further analysis, and a further step in metatranscriptomic of functional genes, is needed.

Responding to the initial question on the role of salt concentration in defining the diversity of the bacterial community in a saline soil, we can say that salinity had the strongest effect on bacterial community structure, as revealed by the study of the correlation between soil properties and bacterial phyla occurrence. Soil pH and other chemical properties seemed to have a minor impact on bacterial group distribution when analysed at the considered spatial scale. The relative abundances of a number of taxonomic groups, as a matter of fact, changed significantly between soil sites according to differences in soil salt content. Nevertheless, the abundance of some other taxa resulted almost unaffected by the salinity level. This may indicate, on the one hand, a high plasticity of bacterial phyla that evidently possess genera and species adaptable to different conditions, whilst on the other hand that the sensitivity to salinity of some groups is poor or, in any case, less dependent on other factors, such as the presence of organic matter, plant roots, etc. Furthermore, it is not certain that bacterial phyla co-occurring at a given site occupy the same ecological niche; rather, the spatial variability can indicate the existence of different scales in the distribution of some major environmental factors, just as the salinity factor. In any case it is evident that the correlation of some groups (*Nitrospira*, *Deferribacteres*, *Spirochaetes*) to the degree of salinity seems to be a necessary condition for the proliferation of the species belonging to those particular groupings.

In conclusion, we feel the need to deepen the scale at which we analyse the bacterial communities in extreme environments. To go back to the more general discussion on saline system ecology, and to the measurement of the "extent of species replacement or biotic change along environmental gradients", which corresponds to the beta diversity sensu, one should distinguish between two rather antithetical phenomena: nestedness and turnover. In the saline soil here studied, we have seen that nestedness occurred only for some taxa, when the biota of a site with a lower number of representatives was a subset of a biota with a greater number of elements of the same taxa (i.e. *Bacteroidetes*, *Chloroflexi*, *Chlorobi*, *Gemmatimonadates*). In this case, the dissimilarity between two sites is related to the difference in specific richness, and it occurs even in the absence of a real turnover of species. In contrast, the spatial turnover implies that the replacement of some species by others can easily occur in a mutable environment, where rain and water movements can strongly change the distribution of salts, although it requires a different experimental scheme, with time-related samplings.

It appears evident that the assortment and distribution of microorganisms in a heavily fragmented environment depend on very complex dynamics of colonization and dispersion and that the analysis of the correlation between the population of microorganisms and environmental parameters, such as the organic matter, pH and salinity, adds important information that can help to unravel the mechanisms of formation and structure of the bacterial communities.

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Multifunctional Agroforestry Systems for Bio-amelioration of Salt-Affected Soils

Y.P. Singh

1 Introduction

Land use options that increase livelihood security and reduce vulnerability to climate and environmental change are necessary. Traditional resource management adaptations, such as agroforestry systems, may potentially provide options for rehabilitation of salt-affected soils and improvement in livelihoods through simultaneous production of food, fodder and firewood as well as mitigation of the impact of climate change (Pandey et al. 2007). Reframing the challenge in another way, agroforestry systems may provide part of the answer to a challenge for sustainability on how to conserve forest ecosystems and farmland biodiversity as well as the services that they provide while simultaneously enhancing food production for an increasing population under the condition of land and water scarcity.

Worldwide, salt-affected areas are estimated to range from 340 million ha to 1.2 billion ha (FAO 2007). Millions of hectares of these salt-affected soils are suited for agricultural production but are unexploited because of salinity/sodicity and other soil and water-related problems. According to FAO, salinization of arable land will result in 30–50 % land loss in the next 25 years to year 2050 if remedial actions are not taken. In India salt-affected soils occupy about 6.73 million hectares and 3.60 million hectares is sodic soils. Indo-Gangetic plains that lie between 21°55′–32°39′N and 73°45′–88°25′E comprising of the states of Punjab, Haryana, Uttar Pradesh and part of Bihar (North), West Bengal (south) and Rajasthan (north) have about 2.7 million hectare salt-affected soils. This area is progressively expanding because of improper soil and water management and development of waterlogging and soil salinization upon introduction of irrigation in arid, semiarid and subhumid regions. Rise in the water table is inevitable upon introduction of irrigation network

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without provision of adequate drainage. Appropriate policy responses combining the agroecosystems as key assets can strengthen adaptation and help to build the resilience of communities and households to local and global changes. Trees growing in combination to agriculture as well as numerous other vegetation management regimes in salt-affected soils can be integrated to take advantage of services provided by adjacent natural, seminatural or restored ecosystems.

Increasing the livelihood security and reducing the vulnerability call for societal adaptation. Such adaptations are possible when combined with traditional resource management systems. Agroforestry as a local adaptation, therefore, is a promising area of interest for scientists, policy-makers and practitioners. This paper presented the contribution of agroforestry systems as a potential option for (1) restoring of salt-affected soils, (2) mitigating climate change, (3) enhancing the fertility status of soil, (4) producing biomass and bioenergy and (5) providing social and economic well-being of the people.

2 Origin and Distribution of Salt-Affected Soils in India

Salt-affected soils are commonly found in Indo-Gangetic plains of Uttar Pradesh, Punjab, Haryana, Rajasthan, Bihar and West Bengal. There are various reasons associated with the formation of salt-affected soils that are both natural and anthropogenic. The geological deposition of clay minerals comprises quartz, feldspars (orthoclase and plagioclase), muscovite, biotite, chloritized biotite, tourmaline, zircon and hornblende in their sand fractions (Bhargav et al. 1980). Quartz and feldspars occur distinctly in the salt fraction. However, illite, mixed-layer minerals, vermiculite and chloride are common to both the silt and clay fractions. The mixed-layer minerals vermiculites and smectite in these soils originate from biotite mica. Different workers have reported variable estimates of salt-affected soils in India. According to the latest estimation in India, salt-affected soils occupy about 6.73 million hectares of land, which is 2.1 % of the geographical area of the country (Sharma et al. 2004). Out of 584 districts in the country, 194 have salt-affected soils (Fig. 1).

3 Characteristics of Salt-Affected Soils

Salt-affected soils differ from arable soils with respect to two important properties, viz. the soluble salts and the soil reaction. Soluble salts in soils may influence the crop production through changes in the proportion of exchangeable cations, soil reaction, the physical properties and the osmotic and specific ion toxicity. The replacement of exchangeable Na^+ with Ca^{2+} requires the application of amendments which can either supply soluble calcium ions directly or induce its solubility from the soil constituents. Nutritional imbalance or specific ion toxicity also adversely

Fig. 1 State-wise extent of salt-affected soils in India (million ha). Source: Sharma et al. (2004)

affects the yields. From reclamation and management purpose, the salt-affected soils of India can be placed into *alkali/sodic* and *saline* soils.

Alkali soils contain excess of salts capable of alkaline hydrolysis such as sodium carbonate, sodium bicarbonate and sodium silicate and sufficient exchangeable sodium to impart poor physical conditions to soil and affecting growth of most plants. These soils have saturated paste pH >8.5, exchangeable sodium percentage (ESP) >15 and different levels of salinity (EC <4 dSm^{-1}). The presence of calcium carbonate concretions at about 1 m depth causes physical impedance for root proliferation (Fig. 2a, b).

Saline soils with white salt encrustation on the surface have predominantly chlorides and sulphates of Na^+, Ca^{2+} and Mg^{2+}. The soils with neutral soluble salts have saturation paste pH <8.5. The electrical conductivity of saturation extract (EC) is

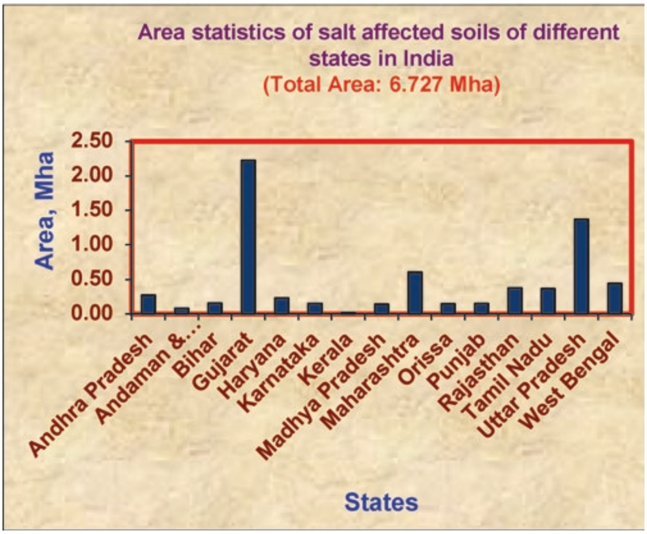

Fig. 1 (continued)

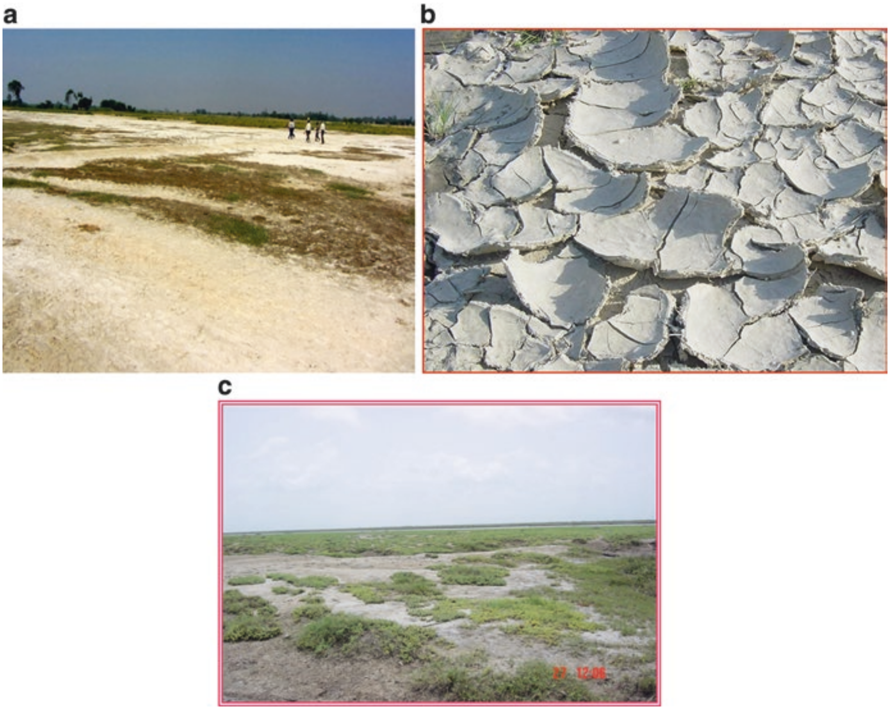

Fig. 2 Typical (**a**) alkali/sodic soil during summer (**b**) after drying and (**c**) saline soil

>4 dSm^{-1} at 25 °C. Such soils invariably have sodium absorption ratio (SAR) of the soil solution >15. The presence of excess neutral salts restricts the plant growth. The main causes of poor growth are high osmotic pressure of soil solution and complex interaction between sodium, calcium and magnesium (Fig. 2c).

4 Selection of Multifunctional Tree Species for Salt-Affected Soils

The initial establishment including germination and initial growth of tree seedlings in saline and sodic environment is a difficult task for researchers. The selection of suitable tree species for high biomass and bioenergy production in salt-affected soils depends upon the tolerance of the species to salinity and sodicity, suitability to local agro-climate and purpose of plantation. Several studies have been conducted to evaluate the performance of a large number of tree species in saline and sodic conditions in India. Yadav (1980) suggested several afforestation techniques and stressed that species like *Prosopis juliflora*, *Eucalyptus tereticornis* and *Acacia nilotica* can grow better on sodic soils. Some preliminary studies have been done to select salt-tolerant species through the pot culture experiments, in which six tree species, i.e. *Casuarina equisetifolia*, *Eucalyptus tereticornis*, *Acacia nilotica*, *Dalbergia sissoo*, *Pongamia pinnata and Araucaria cunninghamii*, were evaluated (Gupta et al. 1988). All of these species failed to grow at the above 61.4 ESP. However, the successful growth was observed at 30.6 ESP for *Acacia nilotica*, *Eucalyptus tereticornis and Casuarina equisetifolia* and at 15.2 ESP for *Dalbergia sissoo*, *Pongamia pinnata* and *Araucaria cunninghamii. Casuarina equisetifolia* showed a moderate salt tolerance. Yadav and Singh (1986) reported a 50 % reduction in the growth of *Acacia nilotica* and *Eucalyptus camaldulensis* at 5.0 dSm^{-1} salinity in clay soil, but they grew satisfactorily at ECe 10.0 dSm^{-1} in sandy soil. However, *Acacia auriculiformis* could not survive beyond ECe 2.5 dSm^{-1}.

Thirty forest tree species were evaluated at high sodicity (pH > 10.0). After 7 years of planting, only 13 out of 30 species survived. Out of these 13 surviving species, only *Prosopis juliflora*, *Tamarix articulata* and *Acacia nilotica* were found suitable for such soils. *Eucalyptus tereticornis* showed good survival and height but no meaningful biomass was observed. However, *Dalbergia sissoo*, *Pithecellobium dulce*, *Terminalia arjuna*, *Kigelia pinnata*, *Parkinsonia aculeata* and *Cordial Rothay* showed more than 70 % survival but could not attain economically suitable biomass (Dagar and Tomar 2002).

The performance of ten tree species in sodic soils having ESP 89 was evaluated at CSSRI, Regional Research Station, Lucknow. After 10 years of field study, only three species, *Prosopis juliflora*, *Acacia nilotica* and *Casuarina equisetifolia*, recorded survival rates of >90 % and attain economical biomass. *Eucalyptus tereticornis* showed good performance during the initial 4 years, but its growth rate declined thereafter. *Azadirachta indica*, *Melia azedarach* and *Dalbergia sissoo*

Table 1 Recommended tree species for the restoration of salt-affected soils

Soil parameter	Firewood/timber/fruit species (common name)
Alkali soils (pH_2)	
>10.0	*Acacia nilotica* (kikar), *Butea monosperma* (dhak), *Casuarina equisetifolia* (Casurina, saru), *Prosopis juliflora* (mesquite, pahari kikar), *Prosopis cineraria* (khejri, jand)
9.0–10.0	*Albizia lebbeck* (siris), *Cassia siamea* (cassia), *Eucalyptus tereticornis* (mysore gum, safeda), *Tamarix articulata* (faransh), *Terminalia arjuna* (arjun)
8.6–9.0	*Azadirachta indica* (*neem*), *Dalbergia sissoo* (sheesham, tahli), *Grevillea robusta* (*silver oak*), *Hardwickia binata* (*anjan*), *Kigelia pinnata* (balam khira), *Morus alba* (mulberry, shahtoot), *Moringa oleifera* (sonjna), *Mangifera indica* (mango), *Pyrus communis* (pear, nashpati), *Populus deltoides* (*poplar*), *Tectona grandis* (teak, saguan), *Syzygium cumini* (jamun)
Saline and waterlogged soils ECe(dSm^{-1})	
20–30	*Acacia farnesiana* (pissi babul), *Prosopis juliflora* (mesquite, pahari kikar), *Parkinsonia aculeate* (Jerusalem thorn, parkinsonia), *Tamarix aphylla* (faransh)
14–20	*Acacia nilotica* (desi kikar), *A. pennatula* (kikar), *A. tortilis* (Israeli kikar), *Callistemon lanceolatus* (bottle brush), *Casuarina glauca* (casuarinas, saru*), C. obese, C. equisetifolia, Eucalyptus camaldulensis* (river red gum, safeda), *Feronia limonia* (kainth, kabit), *Leucaena leucocephala* (subabul), *Ziziphus jujuba* (ber)
10–14	*Casuarina cunninghamiana* (casuarinas, saru), *Eucalyptus tereticornis* (mysore gum, safeda), *Terminalia arjuna* (arjun)
5–10	*Albizia caribaea*, *Dalbergia sissoo* (shisham), *Guazuma ulmifolia*, *Pongamia pinnata* (papri), *Samanea saman*
<5	*Acacia auriculiformis* (Australian kikar, akash mono), *A. deamii*, *A. catechu* (khair), *Syzygium cumini* (jamun), *Salix spp.* (*willow*, *salix*), *Tamarindus indica* (imli)

Source: Dagar and Singh (1994), Gupta Raj et al. (1995) and Singh et al. (2011)

were poor performer. On the basis of available information, a short list of consistently better performing species that could be recommended for saline and alkali soils of Indo-Gangetic plains is given in Table 1.

4.1 Multifunctional Agroforestry Systems

4.1.1 Silvipastoral System

Planting of multipurpose trees with grasses and legumes in an integrated system and their utilization through cut and carry on forage in early years followed by in situ grazing is known as silvipastoral system. From the studies conducted at CSSRI, Karnal, it was found that kallar grass (*Leptochloa fusca*), Rhodes grass (*Chloris gayana*), para grass (*Brachiaria mutica*) and Gutton panic are highly salt tolerant and high biomass producing grass species. Mesquite (*Prosopis juliflora*) and kallar grass silvipastoral practice has been found most promising for firewood and forage production and also for soil amelioration (Singh 1995a, b).

An experiment to evaluate the performance of pastoral, silvipastoral and silvicultural systems was initiated in 1995 at CSSRI, Regional Research Station, Lucknow. Grasses, trees and trees + grasses mixtures were planted in different treatment combinations. The trees have been planted in auger holes of 45 cm dia at the surface and 20 cm at the base and 120–140 cm deep. The pits were filled with a uniform mixture of original soil + 4 kg gypsum + 2 kg UTK + 10 kg FYM + 20 kg silt before planting. The trees have been planted keeping a distance of 5 m between row to row and 4 m between plants. The grass species selected were Karnal grass, Gutton panic, Rhodes grass and berseem. From the study it is concluded that establishment of a *P. juliflora* silvipastoral system with planting of *L. fusca* for 4 years followed by *T. alexandrinum* for 6 years might be a more remunerative land use system than pure pastoral or silvicultural systems (Singh et al. 2014) (Table 2). This system improved the soil to such an extent that less tolerant but more palatable fodder species such as shaftal (*Trifolium resupinatum*), berseem (*Trifolium alexandrinum*) and senji *(Melilotus parviflora*) could be grown under *Prosopis* trees after 74 months (Table 3).

Another silvipastoral model for rainwater conservation and production of fuel and forage from alkali lands has also been developed by Grewal and Abrol (1989). With this model trees such as *Acacia nilotica*, *Eucalyptus tereticornis* and *Parkinsonia aculeata* were planted on ridges, and kallar grass was established in the trenches between ridges. The system conserves rainwater during monsoon, which in turn increased the biomass of trees and intercrop of kallar grass. In addition to firewood and forage production, this system was found useful in checking run-off and soil loss (Table 4).

In addition, tree crops may be used in cattle production systems in order to provide live fences, windbreaks and shade trees and for soil and water conservation purposes.

Table 2 Performance of trees under different agroforestry systems 10 years after planting

Treatments	Survival (%)	Plant height (m)	DBH (cm)	DSH (cm)	Crown diameter (m)
Control (barren)	–	–	–	–	–
L. fusca for 4 years—*P. maximum* for 6 years	–	–	–	–	–
P. juliflora (sole)	90	4.83	6.82	12.84	8.63
A. nilotica (sole)	81	4.53	7.51	12.21	7.20
P. juliflora + *L. fusca* for *4* years—*T. alexandrium* for 6 years	95	5.21	10.10	15.57	8.87
A. nilotica + *L. fusca* for 4 years—*C. gayana* for 6 years	93	5.16	8.22	13.49	7.73
LSD($P < 0.05$)	NS	NS	NS	NS	0.71

Source: Singh et al. (2014)

Table 3 Effect of *Prosopis juliflora—Leptochloa fusca* silvipastoral system on soil properties

Soil properties	Depth (cm)	Initial	After 74 months
pH_2	0–15	10.3	8.9
	15–30	10.3	9.4
EC_2 ($dS\ m^{-1}$)	0–15	2.2	0.36
	15–30	1.5	0.60
Organic C (%)	0–15	0.18	0.58
	15–30	0.13	0.36
Available N ($kg\ ha^{-1}$)	0–15	79	165
	15–30	73	134
Available P ($kg\ ha^{-1}$)	0–15	35	30
	15–30	31	26
Available K ($kg\ ha^{-1}$)	0–15	543	486
	15–30	490	478

Table 4 Rainfall, run-off, soil loss and water balance in flat (FSS) and ridge and furrow planting systems (RFS)

			Run-off (mm)		Soil loss ($Mg\ ha^{-1}$)	
Year	Monsoon rainfall (mm)		FSS	RFS	FSS	RFS
1982	295.1		169.0	204.0	114.73	83.05
1983	584.6		401.3	469.6	23.86	9.39
1984	512.4		337.4	319.7	8.58	1.10
Component (mm)	1982		1983		1984	
	RFS	FSS	RFS	FSS	RFS	FSS
Rainfall	295	295	585	585	512	512
Run-off	0	169	0	401	0	337
Retention	295	126	585	184	512	175
Soil storage	88	58	132	79	216	95
Evaporation	207	69	453	105	269	80

Source: Grewal and Abrol (1989)

4.1.2 Silvi-Agriculture System

In this system the trees are grown for reasonable period of time, followed by growing agricultural crops. Prolonged occupation of alkali soils by trees results in their amelioration in terms of decreased pH and electrical conductivity and improved organic matter and fertility status. Singh (1998) grew wheat and oat in pots filled with topsoils (30 cm) collected from 24-year-old plantations of *Prosopis juliflora*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Albizia lebbeck* and *Terminalia arjuna* on a highly alkali soil and a reclaimed sodic soil. The organic carbon content and nutrient status of the soil under 24-year-old plantations were much higher than that of a farm soil reclaimed through gypsum. Soil amelioration was maximum under *Prosopis* and minimum under *Eucalyptus*. Grain and straw yield of both the crops were maximum under *Prosopis* and minimum under *Eucalyptus* (Table 5).

Table 5 Grain and straw yield of crops under different tree plantations

	Wheat		Oat	
Species	Grain (g/pot)	Straw (g/pot)	Grain (g/pot)	Straw (g/pot)
Eucalyptus tereticornis	32.2	25.3	42.7	58.5
Acacia nilotica	55.7	68.8	61.6	67.5
Albizia lebbeck	45.3	43.5	52.8	66.9
Terminalia arjuna	44.0	38.5	45.8	62.8
Prosopis juliflora	61.7	87.5	87.9	111.1
Crop land	13.3	15.4	24.3	26.7
LSD ($P=0.05$)	2.8	2.0	7.0	9.4

Source: Singh (1998)

Table 6 Promising varieties of fruits for salt-affected soils

Plant types	Promising varieties
Emblica officinalis (aonla)	Chakaiya, NA-6, NA-7, NA-10
Ziziphus mauritiana (ber)	Banarasi Karka, Gola
Psidium guajava (guava)	Shweta and Allahabad Safeda
Punica granatum (Anar)	Ganesh
Morus alba (mulberry)	K-2
Syzygium cumini (jamun)	

4.1.3 Silvi-Horti-Pasture or Horti-Agricultural System

Horticultural species-based agroforestry models for alkali soils have been developed by the Narendra Dev University of Agriculture and Technology, Faizabad. In this model the growth rate of guava + eucalyptus + subabul was faster and production was higher in terms of fruit, fodder and fuelwood. Intercrops of bottle gourd, tomato, cabbage and spinach have been successfully grown in association with guava trees. The fruit species which can be cultivated successfully in alkali soils include *Carissa carandas* (karonda), *Ziziphus mauritiana* (ber), *Emblica officinalis* (aonla), *Syzygium cumini* (jamun) *and Psidium guajava* (guava). Aromatic and medicinal crops such as dill, isabgol, tulsi and matricaria can also be grown as intercrops between fruit trees in case if pH of soil is <9.5. The list of fruit crops suitable for developing horti-pasture system in alkali soils under different situations is given in Table 6.

4.1.4 Sequential Agroforestry System

In this system trees and arable crops are grown in sequence instead of growing them simultaneously. This practice is followed to raise fertility status of the soil, which has gone down either due to continuous cropping or where inherent fertility status of the soil is low, as in sandy desert and salt-affected soils. Short-duration, fast-growing and nitrogen-fixing trees like *Sesbania*, *Leucaena*, *Cajanus* etc. grown for 4–5 years are cut for fuelwood or forage, and the soil is used for arable farming. Rao and Gill (1990) studied this land-management system from 1985 to 1990 on a reclaimed alkali soil having surface pH 8.8. *Sesbania* was grown for 4 years followed by rice-wheat cropping system. Only P and Zn were applied to the crops at recommended rates, and the response to applied N was separately determined in plots fertilized differentially with urea-N. Grain yield of the first rice crop was 6.4 t ha^{-1} in *Sesbania* plots without adding additional nitrogen. Similarly, wheat yields averaged 2.2 t ha^{-1} even without any N application in *Sesbania* plots compared with 1.35 t ha^{-1} in the control plots. About 0.85 Mg ha^{-1} additional grains as well as 17 kg ha^{-1} of additional N ha^{-1} was derived from mineralization of organic residues. The residual effect of *Sesbania* was also noticed on the following rice crop. The total N uptake of crops in the control was 142 kg ha^{-1} and in *Sesbania* plots 222 kg ha^{-1}. The organic fertilization was 2.5 times as effective as inorganic N fertilization. Even after growing crops, without adding any N, available N status in *Sesbania* plots was similar to the plots fertilized with 120 kg N ha^{-1}.

4.2 Alley Cropping

Alley cropping, also called hedgerow intercropping, integrates the benefits of fellow period directly into the cropping period. Crops are sown in alleys between rows of trees, usually leguminous. The trees are pruned at regular intervals, at about 0.6 m aboveground level, and the pruned materials are used for mulch or animal meal. The main purpose of alley cropping is to exploit the soil improvement potential of MPTs for maintaining or even increasing crop production. But production of fodder and fuelwood has also been an objective in many alley cropping trials in India. It is a quite flexible technology that benefits crop and livestock activities and can, through a modification of tree management techniques, provide fuelwood for the household. It is a system that can be adapted to meet particular priorities of an individual farmer. *Leucaena leucocephala* and *Gliricidia sepium* have been most widely used for alley farming. Now the use of two or more species is recommended to reduce the possibility of pests and diseases completely destroying the production as psyllid pest did to *Leucaena* in a major part of the Asia and the Pacific.

4.3 Functions of Agroforestry Systems

4.3.1 Agroforestry Systems as Carbon Sinks

Land management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere if the trees are harvested, accompanied by regeneration of the area, and sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood. The potential of agroforestry systems as carbon sink varies depending upon the species composition, age of trees and shrubs, geographic location, local climatic factors and management regimes. The growing body of literature reviewed here indicates that agroforestry systems have the potential to sequester large amounts of above- and belowground carbon compared to treeless farming systems (Singh et al. 1993). In order to exploit the mostly unrealized potential of carbon sequestration through agroforestry in both subsistence and commercial enterprises, innovative policies, based on rigorous research results, are required.

Organic carbon in soils and their mineralization can be measured as an index of reclamation of degraded soils. Carbon content in barren sodic soils as a result of plantation can be enhanced by increasing the population density per hectare as observed in *Terminalia arjuna* plantations (Jain and Singh 1998). In saline and alkali soils, mineralization rate is suppressed. The soil carbon varies with state and time depending on the productivity potential of a soil site and harvest impacts on the forest floor carbon pool (Scott et al. 1999).

4.3.2 Enhancing Soil Fertility

Trees in agroecosystems can enhance soil productivity through biological nitrogen fixation, efficient nutrient cycling and deep capture of nutrients and water from soils. Even the trees that do not fix nitrogen can enhance physical, chemical and biological properties of soils by adding significant amount of above- and below-ground organic matter as well as releasing and recycling nutrients in the soil. Maintaining and enhancing the fertility of salt-affected soils to grow food grains as well as tree biomass can help meet the demand in the future. Tree species have the potential to conserve moisture and improve fertility status of the salt-affected soils in agroforestry systems. Alternate land use systems such as agroforestry, agro-horticultural, agro-pastoral and agrosilvipasture are more effective for soil organic matter restoration. The degree of improvement was linked to the total biomass production, annual litter fall and its quality, root spread and weight and the level of management practices (Singh, 1996). The highest litter fall at 10 years of tree growth stage was recorded under *Prosopis juliflora* followed by *Casuarina equisetifolia*, *Acacia nilotica*, *Terminalia arjuna* and *Pongamia pinnata*. The winter months accounted for 40–55 % of total litter fall that was composed of about 75.80 % foliage. The increase in organic carbon content of the surface soil (0–15 cm) in a span of 10 years was about fourfold under *P. juliflora* and *P. pinnata* and about threefold in other species (Singh et al. 2011,Tripathi and Singh, 2005).

4.3.3 Improving Water Quality and Water Use Efficiency

Trees with their comparatively deeper root system improve groundwater quality by taking up the excess nutrients that have been leached below the rooting zone of agricultural crops. These nutrients are then recycled back into the system through root turnover and litter fall, increasing the nutrient use efficiency of the agroecosystems. There is robust evidence that agroforestry systems have the potential for improving water use efficiency by reducing the unproductive components of the water balance (run-off, soil evaporation and drainage). Examples from India and elsewhere show that simultaneous agroforestry systems could double rainwater utilization compared to annual cropping systems, mainly due to temporal complementarily and use of run-off in arid monsoon regions. For instance, combination of crop and trees uses the soil water between the hedgerows more efficiently than the sole cropped trees or crops, as water uptake of the trees reached deeper and started earlier after the flood irrigation than of the *Sorghum* crop, whereas the crop could better utilize topsoil water. Integration of persistent perennial species with traditional agriculture also provides satisfactory drainage control to ameliorate existing outbreaks of salinity. Agroforestry in peri-urban agriculture can also be useful for utilization of sewage-contaminated wastewater from urban systems and biodrainage to prevent waterlogging in canal-irrigated areas.

4.3.4 Soil Reclamation

Various studies have been conducted to monitor the soil dynamics due to afforestation of salt-affected soils. As the tree grows, a large amount of litter is shed on the ground, which during decomposition releases several weak acids (humic and fumic) to lower down the soil pH and EC. Singh et al. (2010) and Singh et al., 2008 observed that the litter production after 10 years of tree growth by *Prosopis juliflora*, *Casuarina equisetifolia*, *Acacia nilotica*, *Terminalia arjuna* and *Pongamia pinnata* was 6.1 Mg ha^{-1}, 5.7 Mg ha^{-1}, 5.4 Mg ha^{-1}, 5.1 Mg ha^{-1} and 5.0 Mg ha^{-1}, respectively.

After 10 years of plantation, a significant improvement in the physical properties of the sodic soil was recorded in an experiment conducted at Shivri research farm at Lucknow, India. The bulk density in 0–75 mm soil layer decreased significantly over the control, whereas porosity and infiltration rate increased. The maximum reduction in bulk density was recorded under *Casuarina equisetifolia* followed by *Pithecellobium dulce*, *Acacia nilotica* and *Prosopis juliflora*; the minimum reduction was recorded under *Azadirachta indica* over the initial value. The bulk density of the surface soil (0–75 mm) under control remained unchanged, whereas under 75–150 mm soil layer, it was slightly improved (Table 7). Soil porosity under 10-year-old plantation at 0–75 mm soil layer increased from 40.7 to 54.3 %. However, under the control plot, soil porosity was almost unchanged. The highest soil porosity at 0–75 mm soil layer was recorded under *Casuarina equisetifolia* and minimum under *Azadirachta indica.* There was significant improvement in the infiltration rate under tree plantation over the control and initial values. The highest infiltration rate after 10 years of tree plantation was recorded under *Prosopis juliflora* followed by *Casuarina equisetifolia*, *Pongamia pinnata*, *Pithecellobium dulce*, *Acacia nilotica*, *Azadirachta indica*, *Terminalia arjuna*, *Prosopis alba*, *Eucalyptus tereticornis* and *Cassia siamea*.

Table 7 Ameliorative effect of different tree species on physical properties of soil 10 years after plantation

Tree species	Bulk density (Mg m^{-3})		Soil porosity (%)		Cumulative infiltration rate (mm day^{-1})
	0–75 mm	75–150 mm	0–75 mm	75–150 mm	
Terminalia arjuna	1.47	1.52	44.5	42.6	21.20
Azadirachta indica	1.48	1.56	44.1	41.1	21.70
Prosopis juliflora	1.32	1.46	50.2	44.9	26.30
Pongamia pinnata	1.36	1.57	48.6	40.7	24.30
Casuarina equisetifolia	1.21	1.42	54.3	46.4	25.80
Prosopis alba	1.37	1.61	48.3	39.2	20.00
Acacia nilotica	1.29	1.58	51.3	40.4	21.90
Eucalyptus tereticornis	1.38	1.51	48.0	43.0	19.70
Pithecellobium dulce	1.25	1.58	52.8	40.4	23.10
Cassia siamea	1.46	1.48	45.0	44.1	15.80
Natural fallow	1.50	1.57	43.4	40.7	11.80
Initial	1.57	1.60	40.7	39.6	2.10
LSD ($P \leq 0.05$)	0.08	0.11	3.26	0.76	6.34

Source: Singh et al. (2011)

Biological properties of the soil are largely affected by microorganism status in the soil and nutrients held by these organisms. Soil microorganisms are the most active fraction of soil organic matter and therefore play a central role in the fellow of plant nutrients in ecosystems. They constitute a transformation matrix for organic materials in the soil and act as a labile reservoir for plant available N and P (Jenkinson and Ladd 1981). Forest growth over 40 years has reclaimed the soil in many properties (Singh & Gill, 1992). Several soil characteristics were studied comparatively in forest as well as non-forested sodic soils of the surrounding area to observe the degree of reclamation in the degraded sodic soil. Microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) decreased significantly from the surface to a depth of 45 cm (Table 8). This decrease was about 90 % (MBC) and 65 % (MBP) from the surface soil. The mean MBC up to 0–45 cm depth was 131 μg g^{-1} in forested soil which was approximately three times greater than non-forested sodic soils. Microbial biomass carbon, nitrogen and phosphorus varied significantly between forested and barren sodic soils.

4.4 Biomass and Bioenergy Production

To find high biomass producing tree species for sodic soils, long-term experiment was conducted on highly sodic soils ($pH > 10.0$); at Shivri research farm of Central Soil Salinity Research Institute, *Prosopis juliflora* gave the maximum dry biomass

Table 8 Biological properties of forested (F) and non-forested sodic (C) soils (μg g^{-1})

Character	State	Depth (cm) 0–15 mean ± SD	15–30 mean ± SD	30–45 mean ± SD	Mean	LSD_{05}
MBC	F	285.33 ± 87.66	55.0 ± 33.15	33.33 ± 13.57	124.55 ± 44.79	15.0
	C	89.33 ± 6.65	32.0 ± 9.16	19.66 ± 4.61	46.99 ± 2.27	
MBN	F	53.16 ± 3.09	19.93 ± 5.96	10.2 ± 0.75	27.43 ± 2.60	4.37
	C	14.33 ± 3.76	8.26 ± 0.11	4.96 ± 0.77	9.18 ± 1.94	
MBP	F	25.76 ± 7.0	15.53 ± 4.31	10.66 ± 2.24	17.31 ± 2.38	7.0
	C	9.7 ± 3.81	5.53 ± 0.76	4.13 ± 1.17	6.45 ± 1.65	

Source: Singh and Goel (2012)

Table 9 Biomass production of different tree species in sodic soils

Species	Tree biomass (t ha^{-1}) Stem	Branch	Leaf	Total	Total energy (GJha^{-1})
Terminalia arjuna	23.78	10.70	7.13	41.62	933.53
Azadirachta indica	11.17	6.21	1.84	19.22	520.66
Prosopis juliflora	27.73	26.60	2.17	56.50	1267.75
Pongamia pinnata	9.05	14.45	3.10	26.60	576.85
Casuarina equisetifolia	28.60	9.15	4.35	42.10	934.11
Prosopis alba	14.70	11.10	1.95	27.75	607.13
Acacia nilotica	22.15	26.14	2.46	50.75	1206.32
Eucalyptus tereticornis	24.40	5.27	2.10	31.77	662.12
Pithecellobium dulce	23.50	6.81	1.94	32.25	696.26
Cassia siamea	14.30	5.65	1.70	21.65	466.89
$LSD(P \leq 0.05)$	2.43	4.63	1.21	5.42	

Source: Singh et al. (2010)

with about 96 % biomass allocated to stem and branch wood followed by *Acacia nilotica* with 95 % biomass in wood components (Singh et al. 2010) (Table 9). This is because of their fast growth and higher yields in sodic soil. The highest portion of dry biomass in stem part was recorded with *Eucalyptus tereticornis and Pithecellobium dulce*, respectively, because of less number of branches, whereas the share of dry biomass through branches was higher in *Pongamia pinnata*, while *Terminalia arjuna* showed relatively high proportion of foliar biomass because of broad laminar morphology.

In a long term field study conducted at Shivri research farm, Lucknow, India, Singh et al. (2011) reported that the leaves had slightly higher heat of combustion, whereas it was lowest in stem (Table 9). The calorific values of stem and branches exhibited less variation, with *Acacia nilotica* having the highest heat combustion in both stem and branches, respectively. The differences in total energy production and its allocation to different plant parts led to variation between biomass yield and its allocation to stem, branch and leaves per hectare. *Prosopis juliflora* gave the highest energy harvest followed by *Acacia nilotica* and the lowest by *Azadirachta indica.*

4.5 Replacement of Cow Dung and Nutrients

As a substitute for firewood, a large quantity of cow dung is burnt as fuel in rural India. Abrol and Joshi (1984) calculated that roughly 112 and 90 Mg cow dung can be saved by raising 1 ha plantation of acacia and eucalyptus, respectively, on alkali soils (Table 10).

The cow dung thus saved can be used for upgrading fertility status of alkali soils. The nitrogen saved in the form of animal dung can meet the demand for this nutrient for about 21–26 ha by raising 1 ha of either eucalyptus or acacia plantation. They further estimated that for every ton of dung cake burnt, approximately 70 kg food grains are lost. These estimates indicate that nearly 7.84 ton food grains can be augmented by raising 1 ha of acacia for firewood and adding saved animal dung for crop production. Such benefits from extending agroforestry on salty lands will considerably increase the standard of living and purchasing power of rural work force and provide a base for economic development that will help alleviate poverty in the country. Moreover, such programmes will improve the distorted ecological balance for survival of the mankind.

4.6 Employment Generation

The role of agroforestry in providing employment, particularly in the rural areas where there is often serious unemployment and poverty, is an important consideration in assessing the development value. Abrol and Joshi (1984) estimated that roughly 216 man-days ha^{-1} are needed for initial establishment of forest on alkali soils. For raising acacia and eucalyptus for 7 years, approximately 1092 and 940 man-days are needed, respectively.

Table 10 Direct and indirect benefits from raising 1 ha forest on alkali soil (tons)

No.	Variable	Acacia	Eucalyptus
1	Increase in fuelwood production	68.00	40.00
2	Saving of animal dung cake[a]	112.00	90.00
3	Increase in food production[b]	7.84	6.30
4	Saving of soil nutrients[c]		
	(a) Nitrogen	0.40	0.32
	(b) Phosphate	0.17	0.14
	(c) Potassium	0.22	0.18

[a]1 Mg fuelwood is estimated to replace roughly 2.24 Mg animal dung cake
[b]1 Mg animal dung is estimated to add nearly 70 kg food grain production
[c]1 Mg animal dung cake is estimated to supply roughly 3.5, 1.5 and 2.0 kg of N, P and K, respectively

5 Criteria for Evaluating Agroforestry Systems

The basic attributes of all agroforestry systems are:

1. Productivity (production of preferred commodities and outputs)
2. Sustainability (maintaining long-term productivity without degradation of the natural resource base on which that production is dependant)
3. Adoptability (acceptability of the system by the target clientele and the amenability of the system to adapt itself to prevailing social conditions)

It then follows that the criteria for evaluating agroforestry systems should be based on these attributes.

5.1 Productivity Evaluations

The obvious approach would be to express productivity of the different outputs in measurable, quantitative and meaningful terms. Economic yields of different species are a very common and easily understandable productivity measurement. But the noncomparable nature of different products puts a serious limit to the applicability of this approach to comparison of structurally dissimilar systems.

Calculation of the economic value of the different products gives another easily understood basis of evaluation. In a vast county like India with distinctly different agro-ecological regions, such economic calculations based on the local market value of the products are a good method of comparing systems from different areas. But the main drawback of this method is that many of the products of indigenous agroforestry systems are of a nonmonetary nature. Moreover, many of the products are consumed at the point of production; they do not enter even the local markets.

In agronomic and ecological research, scientists use land equivalent ratio (LER) as a basis of comparing the productivity of different systems. It was originally proposed as a means of comparing the performance of species in an intercropping situation with its performance when grown as a sole crop, and it is so called because it refers to the relative land requirements of intercropping versus monocropping (Mead and Willey 1980). Various modifications have been proposed to the concept (Hiebsch and McCollum 1987).

5.2 Sustainability Evaluations

Sustainability is now a major issue in all development activities concerned with land management. It is a concept that serves as a rallying theme for environmentalists and agricultural scientists and reflects the changing directions of international development efforts.

However, although much has been said and written about sustainability, it still lacks a universally accepted definition. The World Commission on Environment and Development defined sustainable development as development 'that satisfies the needs of the present without compromising the capacity of the future generations to satisfy theirs' (WCED 1987). The meaning of sustainability is dependent upon the context in which it is applied and on whether its use is based on a social, economic or ecological perspective. Nair (1990) stated that 'sustainability, like agroforestry, can be better explained by liking at the issues underlying the concept, rather than by relying on abstract definitions. In simple, production-oriented systems, sustainability can be considered as the maintenance of production over time, without degradation of the natural base on which that production is dependent'.

Since sustainability deals with the long-term productivity, the ecological, social and economic cost associated with maintaining productivity is important. Thus, sustainability evaluations will be interlinked with the other two evaluation criteria (productivity and adoptability). Therefore, the main issues related to sustainability for our discussion here are soil-related (ecological) parameters. Table 11 gives a summary of the present state of knowledge about the effect of trees on soils. It becomes imperative therefore that an evaluation procedure for agroforestry systems should evaluate the system(s) in terms of all these soil-related sustainability parameters. But we still do not have fully developed and widely adopted the criteria for measurement of all these parameters. Until these are fully developed, we will continue with anecdotal (qualitative) statements about the sustainability of agroforestry systems.

Table 11 Soil-related sustainability parameters of agroforestry

	Scientific evidence	
Factor/parameter	Direct	Indirect
Beneficial effects		
1. Organic matter addition	×	
2. Erosion control	×	
3. Improvement of physical properties		×
4. N fixation	×	
5. Improved nutrient cycling	×	
6. Synchrony in nutrient availability		×
7. Moisture availability	×	
8. Soil reclamation		×
9. Improved nutrient availability	×	
Adverse effects		
1. Moisture competition		×
2. Nutrient competition		×

5.3 Adoptability Evaluations

As in the case of productivity and sustainability evaluations of agroforestry systems, there are no widely adoptable criteria for adoptability evaluation as well. Of course, it can be argued that indigenous agroforestry systems have stood the test of time, and they need no adoptability evaluation. In such a situation, what is useful is to learn from the farmers as to why they continue to practice such indigenous systems. That information could then be used as the basis for developing adoptability criteria for new technologies.

Muller and Scherr (1990) undertook a review of agroforestry technology monitoring and evaluation in 165 projects worldwide and suggested a planning approach to the design of effective and adoptable project interventions. This approach has three steps: farmer evaluation, field evaluations and field testing. From the same study, Scherr and Muller (1990) suggest that technologies may be intensively monitored on a small number of farms, whereas a larger sample of farms may be monitored periodically but less intensively in the project area. But the lack of available methods for evaluating variables that are specific to agroforestry, particularly the effectiveness and quality of service functions, is a serious drawback that hinders evaluation procedures for assessing adoptability.

In summary, it has been realized that agroforestry systems need to be evaluated on the basis of their productivity, sustainability and adoptability. While adoptability per se is not an important consideration of evaluation of indigenous systems, all three attributes are important for the evaluation of improved systems. However, the precise criteria for such evaluations have not been fully developed yet.

6 Planting Techniques for Successful Establishment of MFTS

In addition to the effect of high sodium on physico-chemical properties of soils and nutritional problems, the tree growth in alkali soils is constrained due to inability of their roots to proliferate through the hard kankar (calcite) pan existing usually at depths below 50–75 cm from the surface. Therefore, even the earlier afforestation attempts resorted to replacement of excavated alkali soil (50 cm deep pits) with normal soil to improve upon their drainage by digging holes (90–150 cm deep) and refilling the holes with a mixture of good soil, FYM and gypsum before planting tree saplings. The method was introduced in 1895 and named 'deep thala system' of plantation. Later, Yadav and Singh (1970), Yadav (1975) and Yadav (1980) concluded that addition of gypsum (50 % GR) and FYM @ 25 kg per pit (90 × 90 cm) was comparable to replacement of the original alkali soil (pH 10.0) with normal soil for the growth of saplings and their survival. The pit planting technique suffers from the disadvantage of higher requirements of amendments, laborious pit digging operation involving more earthwork and non-perforation of roots through calcic horizon

Table 12 Effect of planting methods on tree growth in a waterlogged saline soil

	Subsurface			Ridge trench		
	Height (m)	DSH (cm)	PS (%)	Height (m)	DSH (cm)	PS (%)
Tree species	After 9 years of planting					
Acacia nilotica	6.41	44.6	50			0
Acacia tortillas	5.31	34.3	56	3.11	10.8	25
Leucaena leucocephala	6.91	36.7	50			0
Prosopis juliflora	8.06	55.9	100	6.40	42.5	100
	After 27 months of planting					
	Surface			SPFIM		
Acacia auriculiformis	1.43		13	2.42		65
Acacia nilotica	3.21		69	2.89		95
Casuarina equisetifolia	2.13		46	3.00		95
Eucalyptus amanuensis	2.24		50	3.78		95
Terminalia arjuna	1.83		81	2.00		90

Source: Tomar et al. (1994)

(hard pan). Keeping in these limitations in view, the planting technique has been improved through 'auger-hole technique' at CSSRI, Karnal (Sandhu and Abrol 1981). Here, 100–140 cm deep and 20–25 cm diameter auger holes are dug with a tractor-operated auger, and saplings are planted after suitably amending the dugout soil. The performance of trees planted with this method has been highly satisfactory (Table 12). This method has picked up very well with the foresters because of reduced manual labour costs and speedy operations. In addition to piercing of hard kankar layer, the advantage of this technique includes encouraging and training of deeper routing. Thus, the trees are able to probe deeper soil layers for water and nutrients to sustain their growth.

Under saline soils the tree growth is adversely affected due to reduced water availability with excessive salts along with period waterlogging and poor aeration especially during the monsoon season. To improve the aeration and reduce the water stagnation, the effect planting on high ridges and mounds showed good results. In waterlogged saline soils, the salinity is usually maximum in the surface layers and decreases with depth down to water table. Therefore, to encash the advantage of low salinity and better soil moisture resumes in subsurface layers. Tomar and Gupta (1984–1994) tried the subsurface planting of saplings (at a depth of 30 cm below the surface) and compared it with ridge planting (490 cm high). Substantially, higher salts accumulated in the ridges that resulted in poor survival and sapling growth (Table 12). The performance of trees was better when planted with subsurface method but the need for spot irrigation was the main problem. Minhas et al. (1996) observed that the planting in the sill of furrow (60 cm wide and 20 cm wide) was subsequently used for irrigating the tree saplings. Besides uniform application of irrigation water and reduction of application cost, the subsurface planting and furrow irrigation method helped increasing a low salinity zone below the sill of the furrows.

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Use of Amendments in Ameliorating Soil and Water Sodicity

O.P. Choudhary

1 Introduction

Soil degradation resulting from salinity and/or sodicity is a major environmental constraint with severe impacts on agricultural productivity and sustainability, particularly in arid and semiarid regions of the world. Salt-affected soils are characterized by excess levels of soluble salts (salinity) and/or Na^+ in the solution phase as well as on cation exchange complex (sodicity). These salts and Na^+ originate either by weathering of primary minerals (causing primary salinity/sodicity) or from anthropogenic activities, involving inappropriate management of land and water resources (contributing to secondary salinization/sodification).

Salt-affected soils occur within the boundaries of at least 75 countries (Szabolcs 1994). These soils also occupy more than 20 % of the global irrigated area. Out of 950 m ha salt-affected soils worldwide, more than 60 % are sodic soils. In India also, sodic soils constitute about 70 % of 7.4 m ha of salt-affected soils (Mandal et al. 2010).

Soils with high levels of exchangeable sodium (Na) and low levels of total salts are called sodic soils. Sodic soils may impact plant growth by (1) specific toxicity to sodium sensitive plants, (2) nutrient deficiencies or imbalances, (3) high pH and (4) spread of soil particles that causes poor physical condition of the soil.

Sodic soils tend to develop poor structure and drainage over time because sodium ions on clay particles cause the soil particles to deflocculate, or disperse. Sodic soils are hard and cloddy when dry and tend to crust. Water intake is usually poor in sodic soils, especially those high in silt and clay. Poor plant growth and germination are also common. The soil's pH is usually high, often above 9.0, and plant nutritional imbalances may occur. A soil pH above 8.4 typically indicates that a sodium problem

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exists. The term “alkali” is often used to describe soils that are high in salt, but sometimes people use the term to mean high pH and at other times to mean high sodium. “Black alkali” refers to a sodic soil condition where organic matter has spread and is present as a dusty material on the soil surface.

2 Sodium Hazard

Sodium levels in soil are often reported as the sodium adsorption ratio (SAR). The SAR is determined from a water extract of a saturated soil paste. A SAR value below 13 is desirable. If the SAR is above 13, sodium can cause soil structure deterioration and water infiltration problems. In Indian subcontinent, high sodium levels in soil are expressed as ESP (exchangeable sodium percentage). An ESP of more than 15 % is considered the threshold value for a soil classified as sodic (Table 1). This means that sodium occupies more than 15 % of the soil’s cation exchange capacity (CEC). The sensitive plants may show injury or poor growth at even lower levels of sodium.

In India, Gupta and Abrol (1990) suggested that distinguishable pH for alkali/sodic soils should be 8.2 rather than 8.5. They also pointed out that these soils contain soluble carbonates and bicarbonates such that $Na/[Cl+SO_4]>1$. Moreover, the value of 15 ESP to distinguish alkali soil from non-alkali soil has been considered too high in alkali smectite soil. The threshold value for these swell-shrink clay soils (vertisols) lies between 6 and 10, and thus ESP value of 8 has been observed to be more appropriate for categorizing alkali soils (Minhas and Sharma 2003).

3 Managing Sodic and Sodic Water-Irrigated Soils

There are usually two options for correcting sodic environment:

1. Change the plant (tolerant species/variety) to suit the sodic soil environment.
2. Change the soil sodic environment to suit the plant.

Often, changing the soil is the most difficult of these options.

Table 1 Sodium hazard of soil based on SAR and ESP values

Classification	Sodium adsorption ratio (SAR)/ESP	Electrical conductivity (dS/m^{-1})[a]	Soil pH	Soil physical condition
Sodic	>13/15	<4.0	>8.5	Poor
Saline-sodic	>13/15	>4.0	>8.5	Variable
Saline	<13/15	>4.0	<8.5	Normal

[a]dS/m = mmho/cm

When soils are high in sodium, the goal is to replace the sodium with calcium and then leach the sodium out of the soil profile. There are three possible approaches for doing this:

1. Dissolve the limestone (calcium carbonate) or gypsum (calcium sulphate) already present in the soil.
2. Add calcium to the soil.
3. Add organic amendments.

If free lime is present in the soil, it can be dissolved by applying sulphur or sulphuric acid. Sulphur products reduce the pH which dissolves the lime, thus freeing up the calcium. If free lime or gypsum is not present in adequate amounts, then an external calcium source has to be added.

The most common form of calcium used for this purpose is gypsum. After broadcasting the calcium source on the soil surface, mix it, and make sure adequate moisture is present to dissolve it.

Reclaiming a foot depth of sodic soil on one acre requires approximately 1.7 t of pure gypsum ($CaSO_4.2H_2O$) for each milliequivalent of exchangeable sodium present per 100 g of soil.

Example of gypsum requirement calculation is presented below:

Your soil has a CEC of 18 milliequivalents per 100 g and ESP of 26, and you desire an ESP of approximately 10 following treatment.

ESP of 26 % — desired ESP of 10 % = ESP of 16 — or 16 % exchangeable Na must be replaced with calcium (Ca) to achieve the desirable ESP.

0.16 (16 %) × 18 meq CEC/100 g = 2.88 meq Na/100 g soil that must be replaced.

*1.7 t $CaSO_4$ × 2.88 meq Na = 4.9 t of gypsum.

Thus, about 5 t of pure gypsum per acre would be required to reclaim the top 12 in. of this soil. Be sure to adjust this calculation for lower grades of gypsum and different soil depths.

*As a general rule of thumb, 1.7 t of gypsum is required per meq of sodium.

Once the gypsum is applied and mixed, sufficient quality water must be added to leach the displaced sodium beyond the root zone. Restoration of sodic soils is slow because soil structure, once destroyed, is slow to improve. Growing a salt-tolerant crop in the early stages of reclamation and cultivating in crop residues or manure add organic matter which will increase water infiltration and permeability to speed up the reclamation process.

Adequate drainage is a prerequisite for reclamation of a sodic soil and, after application of gypsum, to facilitate leaching the sodium out with good quality water. Success in reclaiming nonirrigated sodic or saline-sodic soils with gypsum application may be possible on coarse-textured soils that receive precipitation in excess of soil water holding capacity.

Reclamation of sodic soil requires removal of part or most of the exchangeable sodium, improvement of the soil physical structure and lowering of pH value. The exchangeable sodium is replaced by the more favourable calcium ions according to the exchange reactions as given below, and the sodium thus exchanged is leached out of the root zone.

$$2\,Na - X + Ca^{2+}\,(solution) = Ca - X + 2Na^{+}\,(solution)\downarrow$$

where "X" is the exchange complex of the soil.

Calcium needed for this reaction can be furnished by either calcium-based amendment or calcium carbonate present in the soil whose solubility may be enhanced by application of organic amendments or acid formers. Amendments are the materials which provide Ca^{2+} or mobilize Ca^{2+} in the soil for replacing exchangeable sodium to reduce alkalinity (pH) and sodicity (ESP) of the soil. For reasonably quick results, cropping must precede the application of soil amendments followed by leaching for removal of soluble salts from the soil profile.

The amount and type of chemical amendments required to reclaim a sodic soil will depend upon physic-chemical properties of soil mainly pH, EC and ESP, crop tolerance to sodicity and economic condition of the farmers which will dictate the desired level of replacement of exchangeable sodium. Generally, there are two types of chemical amendments:

(a) Soluble sources of calcium: gypsum ($CaSO_4.2H_2O$), calcium chloride ($CaCl_2$) and phosphogypsum (an industrial byproduct)
(b) Acids or acid formers: elemental sulphur, sulphuric acid, sulphates of iron and aluminium, pyrites and lime sulphur

The choice and effectiveness of these two types of amendments will mainly depend upon the presence or absence of $CaCO_3$ in the soil. In the absence of $CaCO_3$, as is the case in non-calcareous soils, only soluble sources of calcium should be used and application of acids or acid formers is not recommended. But when soil contains calcium, both the sources may be used. Although sparingly soluble $CaCO_3$ is a potential source of calcium and is recommended for acid soil reclamation, it is not recommended for the reclamation of sodic soils because its already low solubility decreases further with increase in pH of the soil.

On the other hand, adding calcium sources, such as gypsum, to saline (not sodic) soils only increases the salt content further and aggravates the salinity problem.

3.1 Types of Amendments

Several commercial products are available for amending sodic and saline-sodic soils. The function of amendments is to provide soluble calcium to replace exchangeable sodium adsorbed on clay surfaces. There are two main types of amendments: those that add calcium directly to the soil and those that dissolve calcium from calcium carbonate ($CaCO_3$) already present in the soil.

Calcium amendments include gypsum (hydrated calcium sulphate) and calcium chloride. Gypsum is moderately soluble in water. Calcium chloride is highly water soluble and fast acting, but it generally is too expensive for most situations.

Table 2 Relative quantities of different amendments compared with gypsum

Amendment	Tonnes equivalent to 1 tonne of gypsum
Sulphur	0.18
Lime sulphur	0.75
Sulphuric acid	0.57
Iron sulphates ($FeSO_4.7H_2O$)	1.62
Aluminium sulphate ($Al_2(SO_4)_3.18H_2O$)	1.27
Limestone ($CaCO_3$)	0.58

Acid-forming or acidic amendments include sulphuric acid and elemental sulphur. Sulphuric acid reacts immediately with the soil calcium carbonate to release soluble calcium for exchange with sodium. Elemental sulphur must be oxidized by soil bacteria and react with water to form sulphuric acid. The formation of sizeable amounts of sulphuric acid from elemental sulphur may take several months to several years. Calcium carbonate must be present in the soil when acid or acid-forming amendments are added.

Choose the amendment mainly on the basis of the cost of the soluble calcium furnished directly or indirectly by the amendment and the speed of the reaction. Also consider ease of application (Table 2).

3.2 *Chemical Reactions of the Commonly Used Amendments*

(a) Gypsum:

$$CaSO_4 + 2NaX = CaX + Na_2SO_4\,(\text{Leachable})\downarrow$$
Sodic soil

(b) Calcium chloride:

$$CaCl_2 + 2NaX = CaX + 2\,NaCl\,(\text{Leachable})\downarrow$$
Sodic soil

(c) Sulphur:

The first step is a biological oxidation of elemental sulphur that is facilitated by aerobic *Thiobacilli* group of chemoautotrophs. In some areas with cold winters, sulphur oxidation is too slow to give satisfactory results.

$$2S + 2H_2O + 3O_2 = 2H_2SO_4$$

(d) Suplhuric acid in a calcareous sodic soil:

$$H_2SO_4 + CaCO_3 = CaSO_4 + H_2O + CO_2$$

Or sulphuric acid can react with two molecules of $CaCO_3$ yielding equivalent of two soluble calcium for each equivalent of acid such as:

$$H_2SO_4 + 2CaCO_3 = CaSO_4 + Ca(HCO_3)_2$$

In practice, therefore, only 1.5 equivalents of calcium can be expected from one equivalent of acid.

(e) Pyrites:

Pyrites (FeS_2), like elemental sulphur, first oxidize into an acid, which in turn reacts with soil lime to yield soluble calcium:

$$2FeS_2 + 2H_2O + 7O_2 = 2FeSO_4 + H_2SO_4$$

$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$

$$2Na-X + CaSO_4 = Ca-X + Na_2SO_4 \downarrow \quad \text{(Leachable)}$$

The rate of oxidation of pyrites is slow; however, its maximum oxidation can be ensured by storing the freshly mined pyrites for a period of 15–20 days in a well-aerated but covered place under moist conditions (preferably 10 % moisture). The efficiency of pyrites enhances when it is applied on the basis of its water soluble sulphur content. Best reclamation results are obtained when pyrites contain 4–6 % water soluble sulphur and its pH is <3.

In some areas, cheap acidic industrial wastes may be available which can be profitably used for sodic soil improvement. Pressmud, a waste product from sugar factories, is one such material commonly used for soil improvement. It contains either lime or some gypsum depending on whether the sugar factory is adopting carbonation or a sulphitation process for the clarification of juice. It also contains variable quantities of organic matter.

Because of its high solubility in water, calcium chloride is the most readily available source of soluble calcium but it has rarely been used for reclamation because of its high cost. Similarly iron and aluminium sulphates are usually too costly and are not used for any large-scale improvement of sodic soils. Large-scale use of sulphuric acid for improving sodic soils is generally not recommended because of handling and application difficulties associated with the large volumes of these acids at the field level.

3.3 Gypsum as Amendment

Mined gypsum is the most commonly used chemical amendment for sodic soil reclamation because of its abundant availability and low cost. Gypsum is chemically $CaSO_4.2H_2O$ that occurs extensively in natural deposits. In India, gypsum deposits are estimated to be more than 1000 million tonnes. It must be ground before it is applied to the soil. Gypsum reclaims the sodic soils to improve crop productivity. It reacts with both the Na_2CO_3 and the adsorbed sodium as follows:

$$Na_2CO_3 + CaSO_4 = CaCO_3 + Na_2SO_4\,(\text{leachable}) \downarrow$$

$$2Na - \text{clay micelle} + CaSO_4 = Ca - \text{clay micelle} + Na_2SO_4\,(\text{leachable}) \downarrow$$

3.4 Application Method

Amendments like gypsum are normally applied broadcast and then incorporated with the soil by disking or ploughing as it is more effective in the removal of exchangeable sodium than gypsum applied on the soil surface. Also mixing limited quantities of gypsum in shallower depths is more beneficial than mixing it with deeper depths. Deeper mixing exposes gypsum to react with Na_2CO_3 of the soil resulting in lesser reduction in ESP throughout the depth. This can decrease the seed germination rate and consequently the crop yield. In shallow mixing, soluble carbonates move down with the wetting front without reacting with applied gypsum.

For improving sodic soils with hardpans or dense clay subsoil layers, deep ploughing (up to 100 cm) has been found to be a useful practice. Improvements in crop yields as a result of deep ploughing occurred because of enhanced water intake rates and depth of penetration and nearly doubled the effective available water holding capacity of the subsoil layers.

3.5 Gypsum Fineness and Solubility

Since gypsum is excavated as lumps from deposit sites, it requires grinding before it can be used for sodic soil reclamation. The fineness to which gypsum must be ground is a matter of economic consideration. It is often said that the finer the gypsum particles, the more effective it would be for the reclamation of sodic soils. But very fine grinding involves higher cost. Application of very finely ground gypsum resulted in high initial hydraulic conductivity of a sodic soil with free soluble carbonates but it decreased sharply with time. On the other hand, treatment with gypsum passed through 2 mm mesh and having a range of particle size distribution helped in maintaining soil permeability at higher level and for a longer period. Higher solubility of finer particles caused them to react with free sodium carbonate, thus inactivating the soluble calcium due to the formation of insoluble calcium carbonate, thereby lowering the efficiency of the applied gypsum in the long term. Therefore, gypsum passed through 2 mm sieve and with a wide particle size distribution is likely to be more efficient.

In many cases, the common practice is to apply sufficient amendment to remove most of the adsorbed sodium from the top 6–12 in. of soil. This improves the physical condition of the surface soil in a short period of time and permits the growing of crops. Continued use of good quality irrigation water, proper irrigation methods and cropping practices further displaces adsorbed sodium. In some cases, it may be necessary to restore the soil to greater depths to obtain adequate drainage and root penetration.

4 Biological Reclamation

Sodic soils are generally low in organic matter. Addition of organic materials and crop residues in the soil help to improve and maintain soil structure, prevent erosion and supply essential plant nutrients besides reclaiming sodic soils. Organic materials and the action of plant roots enhance biological activity in soil. Organic amendments on decomposition result in high partial pressure of CO_2 and produce organic acids. These processes help to increase electrolyte concentration, mobilize calcium through enhancing the solubility of soil calcite and lower pH and ESP of the soil. Most commonly used amendments are crop residues, farm yard manure (FYM), green manure, poultry manure, etc.

The effectiveness of any organic amendment depends upon the amount of CO_2 produced and the reduced conditions. To achieve maximum benefits from application of organic amendments, submerged conditions should be maintained to lower redox potential (i.e. reduced conditions) during the course of their decomposition. Due to their coarse texture and slow decomposition, these organic materials do not allow the pores to be clogged and make the soil porous by maintaining channels and voids which improve water penetration and thereby leaching of the salts out of the root zone.

Generally application of organic materials together with inorganic amendments is cost effective, hasten the reclamation process and increase crop yield; thus, their combined use should be encouraged. Application of FYM at 20 t/ha combined with gypsum will give higher crop yields than gypsum applied alone. However, FYM is economical only when it is available with the farmer locally and free of cost. But when it is to be purchased, then it is not economical than gypsum alone. For biological amelioration alone to be effective, relatively large quantities of organic amendment, i.e. FYM (30–40 t/ha), have to be applied. Further, if the C:N ratio of organic materials is very wide as is the case with sawdust, rice husk and rice straw, these materials decompose slowly and may be less effective than *Sesbania* which has a narrow C:N ratio. Under such circumstances, deficiency of N may be encountered and should be taken care of.

Nevertheless, beneficial effects of straw incorporated in a sodic soil under submerged conditions can be mainly attributed to:

1. The decomposition of organic matter, evolution of CO_2 and certain organic acids
2. Lowering of pH and the release of cations by solubilization of $CaCO_3$ and other soil minerals, thereby increasing the EC
3. Replacement of exchangeable Na by Ca and Mg and thereby lowering the ESP

Organic materials, when applied in conjunction with inorganic amendments or when applied alone in soils of mild sodicity, have proved beneficial and therefore their use in the reclamation of sodic soils occupies an important place.

Incorporating crop residues or ploughing under manure, compost or green manure may improve the tilth and increase water infiltration of sodium-affected soils, especially when combined with other reclamation practices. Deep ploughing to disrupt restrictive claypans and to mix calcium from deeper soil layers has also been used effectively in some situations.

4.1 Reclaiming Sodic Dense Subsoil with Organic Amendments

Subsoil constraints due to sodicity are major limiting factors in crop production in many soils of the world particularly in Australia. In the high rainfall zone of south-west of Victoria in Australia, a survey of subsoil properties in duplex soils found that the clay subsoils were very sodic with exchangeable sodium percentages ranging from 14 to 22 %. Root growth in soil layers is severely restricted and so the clay subsoil below 50–60 cm tends to remain continuously moist, as crops are unable to extract the deep subsoil water. Numerous attempts have been made to ameliorate these subsoil constraints in duplex soils. These have invariably involved deep ripping and the incorporation of high rates of gypsum in the subsoil but with little success (Clark et al. 2007).

A further management option for ameliorating dense clay subsoil is the deep incorporation of organic material into the subsoil layers. Gill et al. (2008), in a field study, examined the effects of deep incorporation of organic and inorganic amendments in 30–40 cm on soil properties, plant growth and grain yield of wheat (*Triticum aestivum* var. Ambrook) on a Sodosol with dense sodic subsoil in a high rainfall region (long-term average annual rainfall 576 mm) of Victoria. Amendments were applied at a rate of 10–20 t ha^{-1}. Deep ripping alone and deep ripping with gypsum did not significantly affect grain yields. In comparison, application of organic materials doubled biomass production and increased grain yield by 1.7 times. Organic amendment-treated plots produced 60 % more grains per area than the untreated control. The crop extracted over 50 mm extra water from below 40 cm soil in organic amendment-treated plots than the untreated control. Nitrogen uptake was almost doubled (403 kg ha^{-1}) in the organic amendment-treated plots than the untreated control (165 kg ha^{-1}). The improved yield with amendments was related to an increase in plant available water in the hostile subsoil and prolonged green-

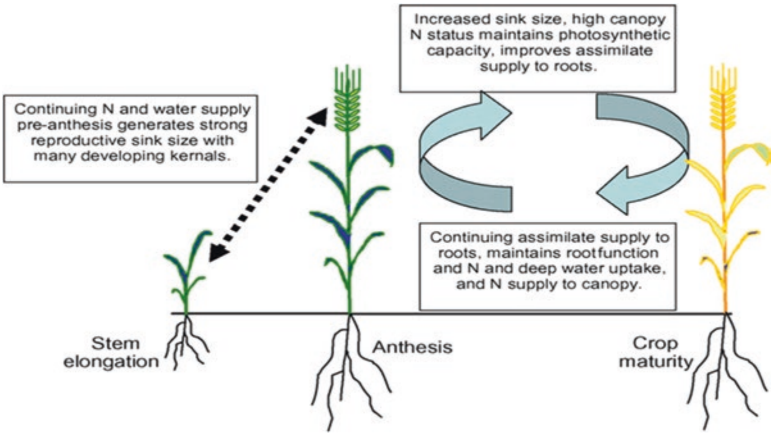

Fig. 1 Proposed scheme of the processes that resulted in delayed senescence where organic amendments were incorporated into the subsoil

ness of leaves and supply of nitrogen and other nutrients. This is perhaps the key to the high grain yields from these treatments. They proposed a series of processes contributed to this outcome and these are outlined in Fig. 1. They all revolve around the provision of:

1. A large and continuing N supply from the organic amendment that led to delayed senescence in the flag leaves involved constructing a large post-anthesis sink strength.
2. Access to deep subsoil water that becomes increasingly available to the wheat plants after anthesis
3. A wheat cultivar that was able to respond to the supply of these resources by producing many large ears, with many spikelets, containing competent florets that developed into kernels.

5 Phytoremediation

Phytoremediation (comprising both vegetative bioremediation and biological reclamation) of sodic and saline-sodic soils is an effective low-cost intervention for resource-poor farmers. When sodic/sodic-water irrigated soils are calcareous, their amelioration can be accomplished through phytoremediation. Phytoremediation involves cultivation of certain tolerant plant species, which help dissolve the native $CaCO_3$ by the plant root action to provide adequate Ca^{2+} for an effective Na^+-Ca^{2+} exchange at the exchange sites. Several researchers have found phytoremediation to be an effective amelioration strategy for calcareous sodic soils with comparable performance against the use of chemical amendments.

5.1 Mechanisms and Processes Driving Phytoremediation

Phytoremediation of calcareous sodic and saline-sodic soils ($Phyto_{Sodic}$) assists in enhancing the dissolution rate of calcite through processes at the soil-root interface resulting in increased levels of Ca^{2+} in soil solution (Qadir et al. 2007). It is a function of the following factors:

$$Phyto_{Sodic} = RP_{CO2} + R_{H}{}^{+} + R_{Phy} + S_{Na}{}^{+}$$

where RP_{CO2} refers to increased partial pressure of CO_2 within the root zone, $R_H{}^+$ is enhanced proton (H^+) released in the root zone in case of certain crops that include legumes, R_{Phy} addresses physical effects of roots in improving soil aggregation and hydraulic properties of the root zone and $S_{Na}{}^+$ represents Na^+ content of shoot, which is removed through harvest of the aerial plant portion. The collective effects of these factors ultimately lead to soil amelioration, provided drainage is present and adequate leaching occurs.

Sodicity levels of calcareous sodic and saline-sodic soils can be achieved through continuous cropping (Qadir et al. 1996; Batra et al. 1997). A number of crops have been tested as phytoremediation tool in these studies including alfalfa, Karnal grass, tall wheat grass, barley and cotton. However, different plant species caused a variable degree and depth of soil reclamation. Using waters containing low salinity and sodicity, most studies demonstrated reduction in soil sodicity levels. Such possibility may be extended to those calcareous saline-sodic and sodic soils where only saline or saline-sodic waters are available for irrigation.

The advantages of this approach are:

1. No investment to purchase chemical amendments is required.
2. There are accrued financial or other benefits from crops grown during amelioration.
3. Soil aggregate stability and porosity are increased as a result of root activity, with subsequent improvement in soil hydraulic properties.
4. Plant nutrient availability in the soil is improved because of organic matter addition by below-ground plant material as well as N fixation when leguminous crops are used.
5. The zone of amelioration is more uniform and deeper, particularly in the case of deep-rooted crops.
6. Carbon sequestration is achieved in the post-amelioration soil.

This plant-assisted amelioration strategy is a promising option to increase the dissolution rate of calcite through processes at the soil-root interface, thereby resulting in enhanced levels of Ca^{2+} in the soil solution.

The comparable effect of phytoremediation with the use of chemical amendments has been attributed to the CO_2 partial pressure (P_{CO2}) exerted by growing plant roots that helped dissolve the soil $CaCO_3$.

1. Dissolution of CO_2 in water:

$$CO_2 + H_2O \rightarrow \; H_2CO_3 \rightarrow H^+ + HCO_3{}^-$$

2. Dissolution of $CaCO_3$ to produce Ca^{2+} as a result of increase in aqueous CO_2:

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + HCO_3^-$$

3. Increased Ca^{2+} concentration in soil solution helps in knocking out Na^+ from the exchange complex.
4. Leaching of the exchanged Na^+ and resultant decrease in SAR and ESP in the root zone.
5. Further, P_{CO2} increases under anaerobic soil conditions compared to aerobic conditions. Hence growing rice crop will decrease sodicity to a greater extent.
6. In addition, organic acids produced due to decomposition of organic matter hasten the reclamation process.

6 Use of Amendments in Ameliorating Sodic and Saline-Sodic Irrigation Effects

6.1 Chemical Amendments

The adverse effects of irrigation with sodic/alkali waters on physico-chemical properties of soils can be mitigated by the application of Ca containing amendments such as gypsum. Unlike native sodic soils, the need for gypsum application for ameliorating the sodic irrigation effects is of the recurring nature. Application of gypsum has earlier been recommended when residual sodium carbonate (RSC) of irrigation water exceeded 2.5 me L^{-1}. However, later researches have shown that factors such as the level of the deterioration of the soil, cropping intensity and the water requirements of the crops will ultimately decide the amount of gypsum required. Sustainable yields of crops in rice-wheat system, irrigated with alkali water (RSC>4), are possible with occasional application of gypsum and FYM. Gypsum to supply 2.5 and 5.0 me L^{-1} to alkali irrigation water for wheat and rice, respectively, was sufficient for maintenance of higher yields. Sodic soils or soils those are previously deteriorated either due to irrigation with alkali water would require gypsum application for neutralizing both soil and irrigation water sodicity. Subsequent application of gypsum is needed on the basis of irrigation water only.

In a long-term experiment (10 years) on sugarcane, Choudhary et al. (2004) observed that the beneficial effect of gypsum was pronounced in increasing cane and sugar yield under sodic (30 %) than under saline-sodic water irrigation (13 %).

Application of gypsum with each irrigation proves better or at least equal in alleviating deleterious effects of RSC waters in rice-wheat system (Bajwa and Josan 1989). The dissolution of gypsum directly in water through the use of gypsum beds or its application to the irrigation channels appears economically attractive, as costs involved in powdering, bagging and proper storage before its actual use are eliminated. Dissolution of gypsum with water passing through these beds is affected by factors such as the size distribution of gypsum fragments, flow velocity, salt content and chemical composition of water. It should, however, be realized that gypsum bed water quality improvement technique may not dissolve more than 8 me L^{-1} of Ca^{2+}; otherwise such an application of gypsum has better potential to improve soil's infiltration rate.

6.2 *Organic Amendments*

It is generally accepted that additions of organic materials improve sodic soil conditions through mobilization of Ca^{2+} from $CaCO_3$ and hasten the reclamation process. In saline environment, beneficial effects of organic materials are mainly attributed to improving soil properties, reduction of osmotic stress and their role in reducing N volatilization losses and enhancing N-use efficiency. Choudhary et al. (2011) observed that continual irrigation with sodic water (SW) resulted in the gradual increase in soil pH and exchangeable sodium percentage (ESP) in a calcareous soil. The cumulative yield loss in SW plots remained <1.5 Mg ha^{-1} for up to 7 years in the case of wheat and up to 9 years in the case of rice. Thereafter, SW resulted in a marked increase in pH and soil sodium saturation and an increased depression in rice and wheat grain yield (Fig. 2).

They conclusively found that with mobilization of Ca^{2+} from $CaCO_3$ during decomposition of organic materials such as farmyard manure (FYM) and green manuring (GM) through *Sesbania aculeata*, the need of gypsum required for controlling the harmful effects of sodic water irrigation can be eliminated in rice-wheat grown in calcareous soils. The application of wheat straw before rice transplanting, although less effective than FYM and GM in increasing rice yield over SW alone treatment, was at par with GM in it residual effect on following wheat yield.

In sugarcane crop, FYM was found to be more effective under saline-sodic (38 %) than under SW irrigation (23 %) (Choudhary et al. 2004). Relative to CW

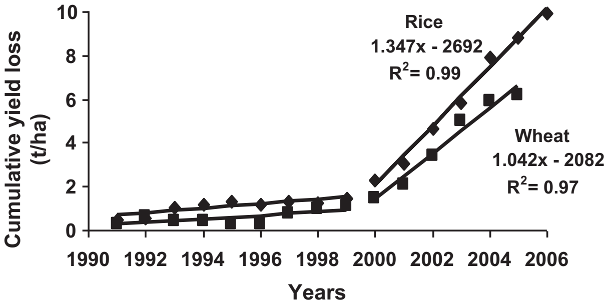

Fig. 2 Cumulative yield loss in response to sodic water irrigation compared to good quality canal water in a calcareous soil over the years. Source: Choudhary et al. (2011)

treatment, there was no decline in yield up to an ESP of 12. An ESP of 10–12 can be maintained under long-term SW irrigation through application of gypsum and FYM. Complimentary effects of these amendments in improving sugar yield were observed under sodic irrigation (12.3 t ha^{-1}). In case of saline-sodic irrigation, sugar yield under FYM treatment (10.8 t ha^{-1}) was at par with gypsum plus FYM treatment but was significantly higher than under gypsum treatment (9.0 t ha^{-1}) advocating that sustainable cane and sugar yields with good quality juice can be obtained by applying gypsum/FYM or both under sodic and only FYM under saline-sodic water irrigation.

7 Future Perspectives

Recent trends suggest that the use of sodic-water irrigated soils for crop production systems will increase in the future. Therefore, an assessment of the impact such use will have on the environment and crop productivity should be made. We need to be aware, therefore, that we cannot simply evaluate the amelioration techniques used solely to reclaim soil sodicity. In order to take a holistic approach, the sustainability of the different soil amelioration methods must also be evaluated (Fig. 3). In fact, such an approach must consider the economic, social and environmental aspects of any amelioration technique. It must also take into consideration several other associated components, including the cost and availability of amelioration inputs (such as water, planting material, amendments and tillage machinery), the level to which a soil's sodicity needs to be reduced and the depth of soil that needs to be ameliorated in order to grow crops subsequently. The quality, availability and cost of the

SUSTAIN**A**BLE *(has a long-lasting, positive impact)*
SI**M**PLE *(is easily manageable by farmers)*
EFFICI**E**NT *(is effective in action)*
LOW-COST *(needs low capital input, is inexpensive)*
ENHANCE FERTIL**I**TY *(increases nutrient availability in soil)*
IMPROVE RHIZ**O**SHPERE *(improves chemical and physical properties)*
PROTECT G**R**OUNDWATER *(avoids groundwater quality deterioration)*
COMP**A**TIBLE *(is suitable for the bi ophysical environment)*
ALLEVIATE POVER**T**Y *(improves the well-being of the farming community)*
ENHANCE Y**I**ELD *(increases crop productivity)*
CONSERVE ENVIR**O**NMENT *(improves the environment, sequesters carbon)*
REPLE**N**ISH SOIL *(restores soil and increases the land's value)*

Fig. 3 Amelioration of sodic and saline-sodic soils: each technique should, ideally, be or do all of the things listed above. Source: Qadir et al. (2006)

water required to produce crops after amelioration must also be factored in, as must the economic value of the crops grown both during and after amelioration. A holistic approach should also consider the nutrient availability status of the soil after amelioration, the long-term sustainability of an ameliorated site in terms of crop productivity, the environmental implications of amelioration with regard to carbon sequestration and any changes that amelioration will be expected to cause in the market value of the land. Finally, socio-economic assessment should be made about the effect that amelioration efforts will have on the livelihoods of the farming communities owning sodic soils.

The interaction between soil management and soil sodicity reclamation under different levels of salinity will continue to be a challenge for researchers, farm advisors and farmers. Sodic-soil management options built on the accumulated wisdom of stakeholders will enhance farmers' participation. Such participatory approaches will ensure that the views and ideas of local people are taken into account. It would create a sense of ownership among the members of the farming community. Community-based sodic-soil management would help to strengthen linkages among researchers, farm advisors and farmers. This will increase the speed with which farmers adopt useful research information. It will also allow farmers to indicate to researchers which research areas are in need of more attention. These linkages will continue to be fostered as the use of sodic soils becomes more common. The development of successful agriculture on these soils will require a greater understanding of the potential of plant species to withstand ambient salinity and sodicity levels in soil and water.

Faced with the challenges associated with sodic soil management, we believe that the time has come to consider such soils a useful resource of economic value rather than an environmental burden. Their use should therefore be considered to be an opportunity to shift from subsistence farming to progressive farming. The restoration of these soils will not only increase productivity but will also provide environmental services by, for example, mitigating the greenhouse effect through enhanced carbon sequestration. Using amendments for sustainable management of soil- and water-induced sodicity represents an excellent opportunity to conserve the environment and make use of such initiatives.

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Phytoremediation of Metal- and Salt-Affected Soils

T.J. Purakayastha, Asit Mandal, and Savita Kumari

1 Introduction

The unscientific disposal of untreated or undertreated effluents has contributed significantly in the accumulation of heavy metals in soil and water bodies. Agriculture practices in the peri-urban areas are very much severely affected by this problem of soil heavy metal contamination. Soil contamination with excessive amount of metals can result in decreased soil microbial activity, soil fertility, and overall soil quality and significant yield reduction (McGrath et al. 1995) and the entry of toxic materials into the food chain (Haan and Lubbers 1983). Salinity and sodicity are among the major causes of land degradation that retards plant growth and productivity worldwide (Qadir and Schubert 2002), and affects roughly 7 % of the world's total land area, particularly in arid and semiarid regions. The effects of higher salt concentrations in soils are marked in plants, which exhibit physiological changes including stomata closure, hyper-osmotic shock, inhibition of cell division, and photosynthesis; however, the most common effects are nutrient imbalance, low osmotic potential, and toxicity of specific ions such as Na^+ and Cl^-, resulting in plant growth inhibition or mortality (Aslam et al. 2011). Although it is necessary to clean up contaminated sites, the application of environmental remediation strategies is often very expensive and intrusive (McGrath et al. 1995). Thus, it is important to develop low-cost and environmentally friendly strategies. In recent years, phytoremediation with the aid of metallophytes is vigorously pursued for remediation of heavy metal-contaminated soils. Phytoremediation or vegetative bioremediation of salt-affected soils can simply be

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defined as the cultivation of salt-accumulating or salt-tolerant plants for the reduction of soil salinity and/or sodicity (Qadir and Oster 2002). The phytoremediation with special reference to "phytoextraction" has lot of implications on remediation of heavy metal- and salt-affected soils. As such, the phytoremediation is a slow process, and therefore it could be repeated several times to reduce the contaminant level to the safe limit. However, the efficiency of phytoremediation can be improved by proper manuring and fertilization, soil amendments, and chelating agents. As phytoextraction process is slow, therefore microbially enhanced phytoextraction is an emerging area of research which uses hyperaccumulator plants in combination with rhizosphere microorganisms for efficient extraction of pollutants especially heavy metals from soil.

2 Food Chain Contamination

The consequences of heavy metals present in available form in the soil have detrimental effect on plant growth and economic produce. Besides adversely influencing plant growth, the toxic effects of heavy metals are amplified along the food chain at each stage of the food web (Fig. 1).

In Indian agriculture, the increased accumulations of heavy metals such as Zn, Ni, Cu, and Fe were observed in different fields containing vegetable and fruit crops which were grown under sewage irrigation from the Keshopur Effluent Irrigation System in Western Delhi (Rattan et al. 2005). The agricultural sustainability of such production system depends to a large extent upon maintaining or enhancing the soil quality, which is rapidly deteriorating due to the disposal of untreated effluents onto it. About 9.5 % of rice paddy soils have been rendered unsuitable for growing rice for human consumption because of high metal contamination. Different doses of heavy metals can cause undetectable, therapeutic, toxic, or even lethal effects. Selenium, copper, and zinc often become toxic as the dose of the metal and exposure to it increases. These metals enter livestock as well

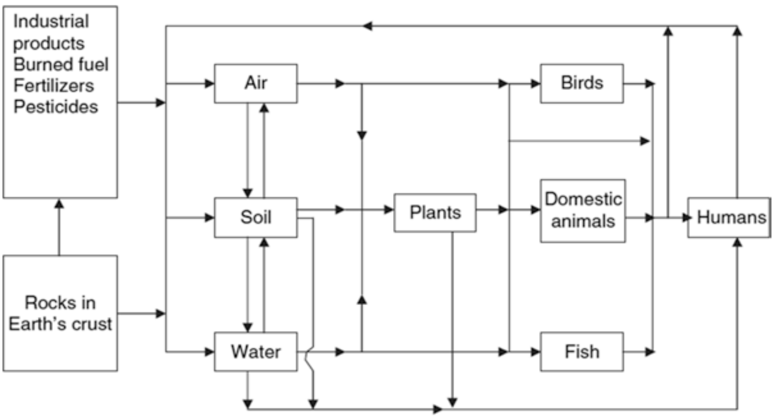

Fig. 1 Heavy metal contamination in the food chain (Purakayastha and Chhonkar 2010)

as our own bodies through the food chain. Zinc toxicity is manifested as gastrointestinal distress, decreased food consumption, anorexia, hemoglobinuria, anemia, poor bone mineralization, and arthritis. Lead poisoning is the most frequently diagnosed toxicological condition in veterinary medicine. Its occurrence has been reported in cattle (Waldner et al. 2002).

3 Remediation Approaches

The remediation processes are classified in physicochemical and biological approaches. The details of remediation processes are described in Fig. 2. The physicochemical approaches are very expensive and intrusive and sometimes disturb the soil biological component. The green approaches of remediation processes are gentle and nonintrusive and economically favorable without disturbing the ecosystem (Vassilev et al. 2004). The techniques of phytoremediation are most frequently found very time consuming and temporarily relieve the problem by immobilizing the metals. The phytoremediation approach involving hyperaccumulating plants to clean up the legacy of contamination including metal and salts is promising as the contaminants are completely removed from the soil system. The microbial approach

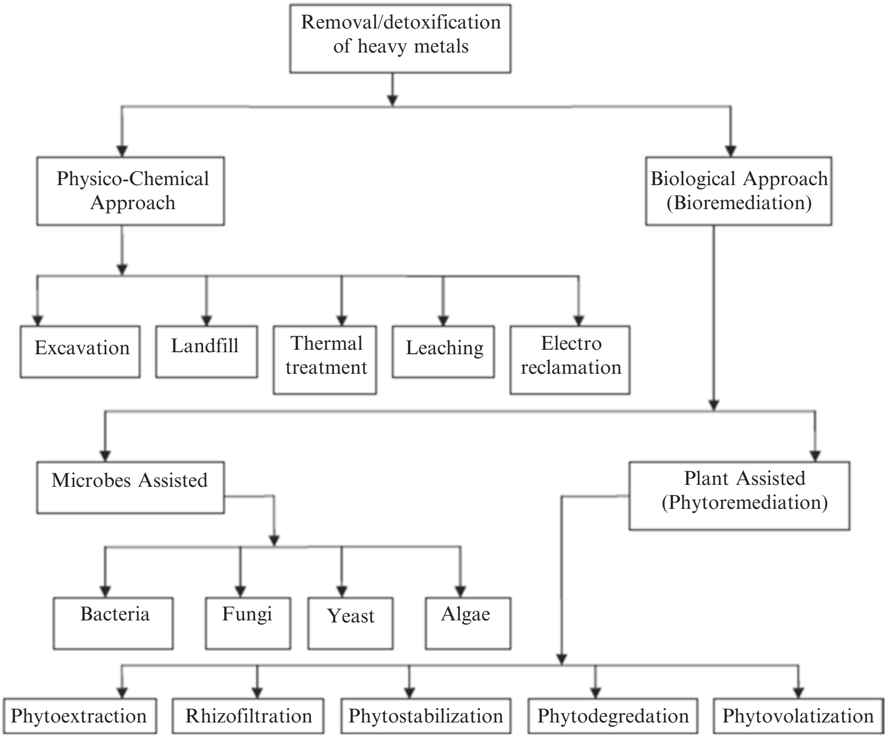

Fig. 2 Methods for remediation of heavy metals from soil (Khan et al. 2009)

alone may not be effective but when it is linked to phytoremediation approaches, then the efficiency of this approach increased.

3.1 Different Approaches of Phytoremediation

Phytoremediation can be practiced in order to scavenge both organic and inorganic pollutants present in solid substrates (e.g., soil), liquid substrates (e.g., water), and the air. There are various phytoremediation approaches that can be employed (Salt et al., 1998):

- *Phytoextraction*. This involves growing plants that are selected for their capacity to concentrate one or more heavy metals on contaminated soil. The plants are then harvested and incinerated, and the ash related to a confined area or the heavy metals are extracted from it.
- *Phytodegradation*. This approach involves the use of plants and associated microorganisms to degrade organic pollutants into less toxic forms or to render them immobilized in order to prevent their entry into the food chain or environment.
- *Rhizofiltration*. This is the use of plant roots to absorb and adsorb pollutants, mainly metals, from water bodies and aqueous waste streams. Artificially created marshes are planted with plant species capable of absorbing or adsorbing metals.

Contaminated water passes through these rhizofilters, and the plants take up heavy metals. The plants are regularly harvested and incinerated. These systems can also be applied to treat sewage effluent:

- *Phytostabilization*. This method uses plants to reduce the bioavailability of pollutants in the environment by reducing leaching, runoff, and soil erosion.
- *Phytovolatilization*. This is the use of plants to volatilize pollutants.

Bioremediation is any process that uses organisms (microorganism, algae, and plant) or their enzymes to manage the polluted environment and return to its original condition either by degrading or transforming toxic, hazardous chemicals to non-toxic form. Phytoremediation has been defined as the use of green plants and their associated microorganisms, soil amendments, and agronomic techniques to remove, contain, or render harmless environmental pollutants (Khan et al. 2009) (Table 1).

3.2 Types of Phytoextraction

1. Natural: where plants naturally take up contaminants from the soil-unassisted
2. Assisted: use of chelating agents, microbes, and plant hormones to mobilize and accelerate contaminant uptake → uptake of contaminants also accelerated by use of hyperaccumulators, e.g., *Thlaspi caerulescens*

Table 1 Different phytoremediation processes

Process	Mechanism	Contaminants	Typical plants
Phytoextraction	Hyperaccumulation	Metals (Pb, Cd, Zn, Ni, Cu) with EDTA addition for Pb, Se	Sunflower, Indian mustard, rapeseed plant
Rhizofiltration	Rhizosphere accumulation	Metals (Pb, Cd, Zn, Ni, Cu) Radionuclides (^{137}Cs, ^{90}Sr, ^{238}U), Hydrophobic organics	Aquatic plants: (pond weed, duck weed); *Hydrilla*
Phytostabilization	Complexation	Metals (Pb, Cd, Zn, As, Cu, Cr, Se, U), Hydrophobic organics (PAHs, PCBs, dioxins, furans, pentachlorophenol, DDT)	Phreatophyte trees to transpire large amounts of water for hydraulic control
Phytovolatilization	Volatilization by leaves	Mercury (Hg), selenium (Se), tritium ($^{3}H_{1}$)	Poplar, Indian mustard, canola
Phytodegradation	Degradation in plant	Herbicides (atrazine, alachlor), Aromatics (BTEX), Chlorinated aliphatics	Phreatophyte trees, poplar, willow, sorghum, clover, alfalfa, cowpeas

Source: Mukhopadhyay and Maiti (2009)

3.3 *Hyperaccumulator Plants*

Hyperaccumulator plants are widely used for the removal of contaminants by the virtue of phytoextraction mechanism and its possible utilization (Fig. 3). Phytoremediation is an eco-friendly technology that heavily depends on the efficiency of the metal hyperaccumulating plants. A plant is classified as a hyperaccumulator when it takes up heavy metals against their concentration gradient between the soil solution and cell cytoplasm and thus acquires the capacity to accumulate a very high metal concentration in tissues without any impact on basic growth and metabolic functions. The phenomenon is viewed as an evolutionary selection process that protects against herbivores and pathogens. The criteria for designating a plant as a hyperaccumulator for different metals are given below:

- Shoot metal concentration (oven dry basis) should be more than 1 % for Mn and Zn; 0.1 % for Cu, Ni, and Pb; and 0.01 % for Cd and As.
- Should be a fast-growing habit with a high rate of biomass production.
- Should be able to accumulate metals, even from low external metal concentrations.
- Should be able to transfer accumulated metals from root to shoot (aboveground) quite efficiently (often with more than 90 % efficiency).

There are many reports on the hyperaccumulating potentials of different species of plants, as mentioned in (Table 2).

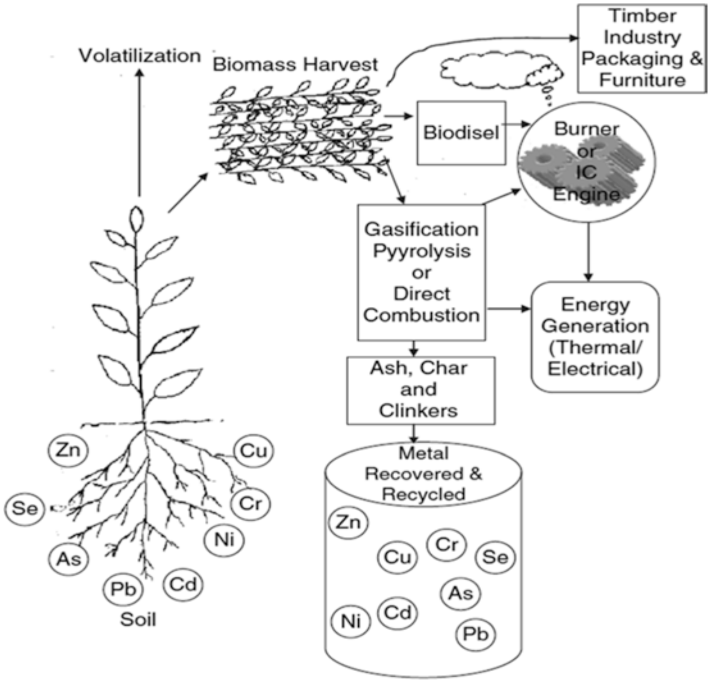

Fig. 3 Phytoextraction of metals from soil and their utilization (from Purakayastha and Chhonkar 2010)

Table 2 Important hyperaccumulators plants used for phytoextraction of heavy metals (from Sinha et al. 2009)

Contaminant	Medium	Plant
Arsenic	Soil	*Pteris vittata* L.
Cadmium	Soil	*Oryza sativa* L.
Chromium	Soil	*Brassica juncea* L.
Copper	Soil	*Elsholtzia splendens*
Lead	Soil	*Chenopodium album* L.
Mercury	Soil	*Marrubium vulgare*
Nickel	Soil	*Alyssum lesbiacum*
Selenium	Soil	*Brassica rapa* L.

4 Phytoremediation of Metal-Contaminated Soil

Several species of *Brassica* are widely reported hyperaccumulator of various metals. In this respect, Purakayastha et al. (2008) screened five species of *Brassica*: (1) *B. juncea* (Indian mustard) cv. Pusa Bold, (2) *B. campestris* (yellow mustard) cv. Pusa Gold, (3) *B. carinata* (Ethiopian mustard) cv. DLSC-1, (4) *B. napus* cv. early napus, and (5) *B. nigra* cv. IC-247 for identifying a suitable species for hyperaccumulation of heavy metals, viz., Zn, Cu, Pb, Ni, and Cd. It was concluded that *Brassica carinata* cv. DLSC-1 could reduce the metal load by 15 % for Zn, 12 % for

Pb, and 11 % for Ni from a naturally contaminated soil from peri-urban Delhi, while *Brassica juncea* cv. Pusa Bold emerged promising that reduced soil Cu content by 21 % in a single cropping. Castor (*Ricinus communis* L.) was reported to accumulate large amount of Ni, and therefore, it could be used as a potential plant for phytoremediation of Ni-contaminated soils (Adhikari and Ajay 2012). Brunetti et al. (2012) studied three species of *Brassica viz.*, *Brassica alba* (L.) Rabenh, *Brassica carinata* A. Braun, and *Brassica nigra* (L.) Koch, for the phytoextraction of Cr, Cu, Pb, and Zn from an unpolluted and polluted silty loam soil added with either *Bacillus licheniformis* BLMB1 or compost or both. Here it was observed that, in particular, Cr accumulation in *B. alba* resulted higher than the Cr threshold for hyperaccumulator plants (1000 mg kg^{-1}). This result provides a new plant resource that may have a potential use for phytoextraction of Cr from contaminated soil. However, because of the low bioconcentration factors (<1) for all studied metals, these species cannot be regarded as suitable for the phytoextraction of excessive Cr, Cu, Pb, and Zn from polluted soils. Thus, these species may be used with success only for low metal-polluted soils.

The commonly used vegetables such as fenugreek (*Trigonella foenum-graecum* L.), spinach (*Spinacia oleracea* L.), and rye (*Brassica campestris* L.) have a great potential to remove Cr contamination in silty loamy and sandy soils (Dheri et al. 2007). The findings established that family Cruciferae (raya) was the most tolerant to Cr toxicity, followed by Chenopodiaceae (spinach) and Leguminosae (fenugreek). Ramasamy (1997) observed that *Jasminum auriculatum* was relatively tolerant up to 1000 μg g^{-1} Cr in soil than *Crossandra infundibuliformis* and *Jasminum sambac*, which were found very sensitive at this concentration. Anandhkumar (1998) examined the level of Cr accumulation in flower plants, viz., *Jasminum sambac* (Gundumalli), *Jasminum grandiflorum* (Jathimalli), *Polianthes tuberosa* (tuberose), and *Nerium oleander* (Nerium) and found that a considerable amount of Cr was accumulated in flower crops due to irrigation with tannery effluent. Shanker et al. (2005) conducted a greenhouse experiment to study the potential of Cr phytoaccumulatory capabilities of four promising agroforestry tree species, viz., *Albizia amara*, *Casuarina equisetifolia*, *Tectona grandis*, and *Leucaena leucocephala*. The results suggested that *Albizia amara* is a potential Cr accumulator with citric acid as soil amendment. Several green house studies were also conducted for the remediation of soils contaminated with heavy metals (Cr, Cd, Pb, and Cr) using different ornamentals and flowering plants (Ramana et al. 2008a, b, 2009, 2012a, b). They identified marigold and tuberose possess the characters of Cd hyperaccumulation, and these two crops could be grown for the phytoextraction of Cd from soils with low to medium level of contamination. Further, chrysanthemum could be useful for phytostabilization of Cd-contaminated soils. Mani et al. (2007) investigated the interaction between Cd and Ca, Zn, and organic matter for Cd phytoremediation in sunflower. The results suggested the phytoremediation of Cd-contaminated soil through soil-plant-rhizospheric processes. The use of phosphorus fertilizer (P) as an amendment can enhance the phytoremediation potential and plant biomass of silverback fern (*Pityrogramma calomelanos*) in arsenic-contaminated soil (Jankong et al. 2007). Some hyperaccumulator plants like Chinese brake fern (*Pteris vittata*) proved best suited remediation of As-contaminated site (Ma et al. 2001). Soil amendments in the arsenic-contaminated soil with phosphatic fertilizers such as diammonium phosphate (DAP) and single superphosphate (SSP) improved the phytoextraction ability of the *Pteris vittata* (Mandal et al. 2012a). The subsequent effect of phytoextraction of arsenic-contaminated soil by *P. vittata* was beneficial for growing rice resulted in decreased As content in rice grain of <1 ppm (Mandal et al. 2012b). The effect of phytoextraction of arsenic-contaminated soil improved the soil microbiological activities (Mandal et al. 2014). Enhanced phytoextraction of heavy metals using chelating agents and metal hyperaccumulators has been proposed as an effective approach to remove heavy metals from contaminated soils. The application of EDTA (5 and 8 mmol kg^{-1}) and citric acid (5 and 8 mmol kg^{-1}) had inhibitory effects on the growth of the plants. However, the addition of chelators effectively enhanced the mobility of target heavy metals (Cd, Cu, Pb, and Zn) in soils and significantly increased the accumulation of these heavy metals in aerial parts of the plants. The concentrations of Cd, Cu, Pb, and Zn increased by 2.37–4.86, 0.09–3.73, 0.33–5.06, and 3.71–6.06 times, respectively, compared to the control (Sun et al. 2009).

It is an established fact that rhizospheric soil supports a larger microbial population than the bulk soil, and these microorganisms possess mechanisms capable of altering the environmental mobilities of metal contaminants, which has subsequent effects on the potential for root uptake. Microbially enhanced phytoextraction of heavy metals from soil is widely reported. In various studies, growth-promoting effects of phosphate-solubilizing bacteria (PSB) are well established both in unpolluted and polluted soils when used as inoculants (Ma et al. 2011). However, the degree of their impact on different plants varies depending upon plant species, bacterial species, soil types, and environmental factors. In metalliferous soils, several researchers have studied phytoremediation using PSB as bio-inoculants to remove different heavy metals from soils. In Table 3, various phytoremediation studies have been listed to show the effects of different PSB using different plant species and metals. Most of the laboratory or greenhouse studies have employed plants of Brassicaseae family in conjunction with PSB because plant species of this family (hyperaccumulator plants) have been reported to accumulate substantial amount of metals in their tissues. Among environmentally toxic metals, only few metals such as Ni and Cu have been studied extensively. Therefore, phytoremediation studies concerning other metals would reveal new challenges, insights, and problems leading to pave ways for further research in these areas.

The canola plants grown in the absence of VAM inoculation reduced the concentrations of Mn, Cu, and Zn in the contaminated soil by 26, 59.4, and 18.4 % in the marginally contaminated sewage soil and by 41.2, 60.7, and 78.3 % in the highly contaminated one (Table 4). The data indicated also that potential toxic elements (PTEs) uptake increased parallel to the increase in their concentration in soil. Growing canola plants in the presence of VAM inoculation caused a reduction in Cu concentration in soil reached 84.0 % and 67.3 % in the marginally and highly contaminated sewage soils, respectively. In association with VAM inoculation, canola plants removed more Zn from the highly contaminated sewage soil.

Table 3 Phosphate-solubilizing bacteria (PSB) mediated metal phytoextraction and plant growth promotion

PSB	Plant	Heavy metals	Role of PSB (phytoextraction)	References
Pseudomonas sp. A3R3	*Brassica juncea*, *Alyssum serpyllifolium*	Ni	Increased significantly the biomass (*B. juncea*) and Ni content (*A. serpyllifolium*) in plants grown in Ni-stressed soil	Ma et al. (2011)
Pseudomonas sp. SRI2, *Psychrobacter* sp. SRS8, *Bacillus* sp.SN9	*Brassica juncea*	Ni	Increased the biomass of the test plants and enhanced Ni accumulation in plant tissues	Ma et al. (2009a)
Psychrobacter sp. SRA1, *Bacillus cereus* SRA10	*Brassica juncea*	Ni	Enhanced the metal accumulation in plant tissues by facilitating the release of Ni from the non-soluble phases in the soil	Ma et al. (2009b)
Pseudomonas sp. TLC6-6.5-4	*Zea mays*	Cu	Significantly increased Cu uptake by plants and also enhanced the biomass of maize	Li and Ramakrishna (2011)

Table 4 Walter's classification of halophytes (from Walter et al. 1961)

Salt excluding	In these plants, the root system possesses an ultrafiltration mechanism, and this characteristic leads to establishment of such species as the dominant component of the mangrove vegetation, for example, *Rhizophora mucronata*, *Ceriops candolleana*, *Bruguiera gymnorrhiza*, and *Kandelia candel*
Salt excreting	These plants regulate internal salt levels through foliar glands, for example, *Avicennia officinalis*, *Avicennia alba*, *Avicennia marina*, *Aegiceras corniculatum*, and *Acanthus ilicifolius*
Salt accumulating	They accumulate high concentrations of salt in their cells and tissues and overcome salt toxicity by developing succulence, for example, *Sonneratia apetala*, *Sonneratia acida*, *Sonneratia alba*, *Lumnitzera racemosa*, *Excoecaria agallocha*, *Salvadora persica*, *Sesuvium portulacastrum*, *Suaeda nudiflora*, and *Pentatropis sianshoides*

In general, plant performance on heavy metal removal and translocation of heavy metals from the roots to the aboveground tissues involved phytoextraction coefficient and translocation factor (TF). Plants with the high phytoextraction coefficient and TF have the potential for metal phytoextraction (Yoon et al. 2006; Nouri et al. 2011). Potential of Cd resistant bacterium for its phytoextraction and translocation in *Helianthus annuus* was studied (Setkit et al. 2014). The study revealed that phy-

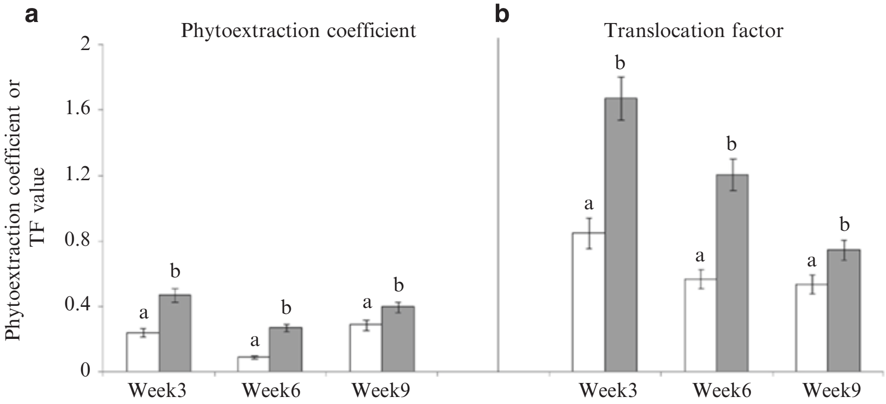

Fig. 4 Sunflower planted in Cd-contaminated soil inoculated with *Micrococcus* sp. MU1 and control (from Setkit et al. 2014)

toextraction coefficient and TF of *H. annuus* L. inoculated with *Micrococcus* sp. MU1 in all collected periods were higher than those of the uninoculated control (Setkit et al. 2014) (Fig. 4). Although *H. annuus* L. is not the best Cd hyperaccumulator due to low phytoextraction coefficient, the oil extracted from *H. annuus* L. seeds without Cd contamination offers economic benefits for reclamation of polluted areas. Interestingly, TFs of *H. annuus* L. inoculated with *Micrococcus* sp. MU1 in all collected periods were higher than those of the uninoculated control. Similar to the phytoextraction coefficient, the highest TF (1.7) were found at 3 weeks after transplant of *H. annuus* L. in contaminated soil with bacterial inoculation.

Chromium content was significantly higher in *Amaranthu*s grown in contaminated soil with *Amaranthus dubius* wild II when compared with contaminated soil with edible *Amaranthus tricolor*, *Amaranthus dubius* wild I and PSB, and control. Significantly higher cobalt content was observed in the *Amaranthus* plants grown in contaminated soil with *Amaranthus dubius* wild I and contaminated soil with *Amaranthus dubius* wild I and PSB. Significantly higher lead content was observed in the *Amaranthus* plant grown in contaminated soil with edible *Amaranthus tricolor* and PSB and contaminated soil with *Amaranthus dubius* wild I treatments, respectively, when compared to other treatments and control.

5 Role of PGPR and mycorrhizae for Cleanup of Heavy Metal-Contaminated Soil

In present agriculture plant growth-promoting rhizobacteria (PGPR) have been extensively used to enhance crop yield and soil sustainability. PGPR is a group of bacteria that colonize plant roots and promote growth and yield (Wu et al. 2005). Very little knowledge has been gained in respect to the mechanisms by which PGPR promote plant growth (Vessey 2003). However, PGPR are known to increase root system uptake properties of rhizobacteria colonized crops by facilitating plant nutrition such as N, P, and Fe. Shen et al. (2006) reported that the mycorrhizal plants could modify the metal transfer from soil to roots and aboveground vegetation by increased biomass and phosphorus nutrition. Mycorrhizal plant species influences metal toxicity to plants through decreasing translocation of heavy metals from soil to biomass.

Rhizosphere is a type of microenvironment where groups of microbes form special type of communities with plant growth-promoting capabilities and remove the toxic contaminants. Metal bioavailability to the plants is enhanced by rhizosphere by releasing of chelating agents, acidification, phosphate solubilization, and redox changes. Thus, interactions between plants and useful rhizosphere microbes can improve biomass production and accumulation of heavy metals at a toxic level. Arbuscular mycorrhizal (AM) fungi are one of the important endophytic fungi living in the roots of most terrestrial plants. There are other beneficial microorganisms present in the rhizosphere that may contribute to the plant tolerance to heavy metal contamination. Many researchers studied about the interaction of plants with AM fungi that can enhance plant tolerance against heavy metals and/or improve plant growth in contaminated sites (Vivas et al. 2003).

6 Salt-Affected Soil

The total area of salt-affected soils in the world is 831million hectares which includes 397 and 434 million hectares of saline and sodic soils, respectively (FAO 2000). Salt-affected soils can be defined as soils with high levels of dissolved salts and/or high concentrations of adsorbed sodium ions in the soil matrix. Soil salinity and sodicity are the most serious limiting factors that affect plant growth and productivity and are the major causes of soil degradation (Qadir and Schubert 2002). Salinity is one of the rising problems causing tremendous yield losses in many regions of the world especially in arid and semiarid regions (Hasanuzzaman et al. 2014). There are two major approaches to encounter the problem of salinized soils: (1) control of salinity level by soil, water, and crop management practices and/or (2) biological or genetic management through the use of high salt-tolerant species. Amelioration of salt-affected soil with various soil chemical amendments is very much expensive in moderate to strong degree of salinity. In the areas of shallow water table and poor natural drainage, artificial drainage is recommended that could be a noneconomic approach. In order to improve the soil fertility of chemically reclaimed salt-affected soil, application of organic fertilizer such as manure, compost and green manure crops were found beneficial. Methods commonly used to combat salinity are either classical or using halophytes.

The mechanisms by which plants remove salt from the soil are illustrated in Fig. 5. The plant root along with microorganisms in the rhizosphere acts together to influence the removal of salts from soil. The two important mechanisms that phy-

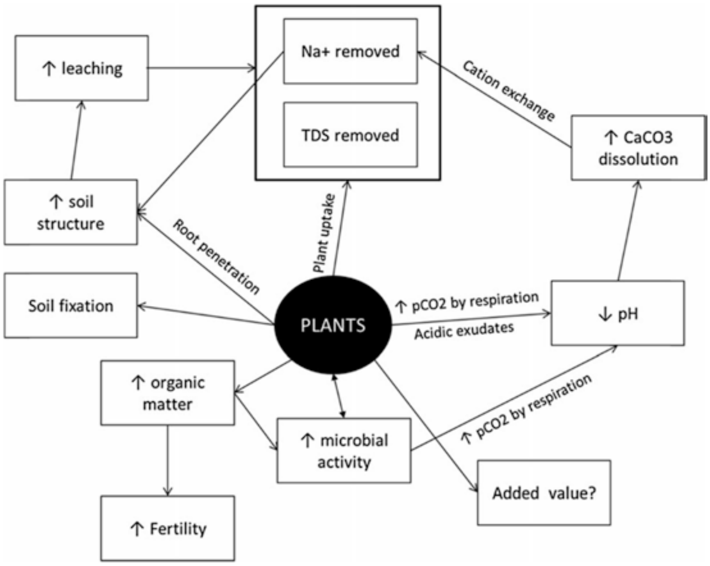

Fig. 5 Role of plants in salt-affected soil remediation and possible variations in soil properties as a result of this process (from Qadir et al. 2000, 2006; Rabhi et al. 2010)

toremediate the salt-affected soils are pH reduction which enhances dissolution of $CaCO_3$ and, therefore, the available Ca^{2+} for cation exchange with sodium (Qadir et al. 2005; Rasouli et al. 2013; Walker et al. 2014), and the second one is plant uptake of dissolved salts in general and/or sodium in particular (Shelef et al. 2012). The additional advantage obtained by enhancing the added value uses the plants as bioenergy crops or for cellulose production (Abideen et al. 2011; Glenn et al. 2013). For practical purposes, however, it is crucial to clarify if plant uptake is or is not a significant mechanism of salt removal, since this may limit the phytoremediation approach to calcareous soils, as well as to situations in which water for leaching is available. Determining minimum data set could be important criteria for soil quality assessment of typical salt-affected farmland (Yao et al. 2013) that may be suitable for risk assessment and remediation.

6.1 Halophytes for the Remediation of Salt-Affected Soil

Halophytes are the plants which are adapted to grow well in high salinity conditions. Halophytes are defined in different ways by many scientists based on different criteria. Schimper (1903) defined halophytes as the plants capable of normal growth in saline habitats and also able to thrive on “ordinary” soil. According to Stocker (1928), they are plants which can tolerate salt concentrations over 0.5 % at any stage of life. More simply, Dansereau (1957) mentioned that plants which grow exclusively on saline soil are halophytes. Greenway and Munns (1980) defined halophytes as follows: "a kind of native flora of saline soils, which contain solutions with a Psi of at least 3.3 bar, being equivalent to 70 mM monovalent salts." Plants that cannot survive in these habitats are classified as non-halophytes. Obligate halophytes grow only in salty habitats. They show sufficient growth and development under high saline condition. Many plant species belonging to Chenopodiaceae family fall in this category. Facultative halophytes are able to establish themselves on salty soils, but their optimum lies in a salt-free or at least low-salt condition. However, they can tolerate salt. Most Poaceae, Cyperaceae, and Brassicaceae species as well as a large number of dicotyledons like *Aster tripolium*, *Glaux maritima*, *Plantago maritima*, and so forth belong to this group.

Plantation with *Atriplex halimus* decreased electrical conductivity for saline-sodic soil from 39.2 to 26.5 $dS.m^{-1}$ and from 6.2 to 4.9 $dS.m^{-1}$ for saline soil. Sodium adsorption ratio (SAR) declined to half and 28.6 % for saline-sodic and saline soils, respectively. This study revealed an increased efficiency of *Atriplex halimus* with increasing salinity which suggest it a good candidate for soil desalination in arid and semiarid regions (Abdul-Kareem and Nazzal 2013). The use of PGPR in the treatment expected to increase by 30–60 % phytoremediation efficiency on salt-impacted sites (Wu 2009). Salt ions, Na^+ and Cl^-, are readily taken up from the soil by plants and transported into plant shoots via the xylem and can only be returned to the roots via the phloem (Tester and Davenport 2003; White and Broadley 2001). Only a small amount of salt ion can be transported back to the roots, suggesting that the transport of Na^+ and Cl^- is somewhat unidirectional and mainly accumulates in aboveground plant tissues.

6.2 Salt Adaptation Mechanism by Plants in Salt-Affected Soil

Based on the different mechanisms of adaptation to salty condition, Walter (1961) has classified the halophytes into three types: (1) salt excluding, (2) salt excreting, and (3) salt accumulating (Table 4).

Complete ionic species of Na^+ and Cl^- is the main concern of salt stress in plants; most studies have concentrated on Na^+ exclusion and the control of Na^+ transport within the plant (Munns and Tester 2008). Halophytes are capable to tolerate high ionic concentration which involves the ability to reduce the ionic stress on the plant by minimizing the amount of Na^+ that accumulates in the cytosol of cells, particularly those in the transpiring leaves (Carillo et al. 2011). Although salt exclusion is a very effective way to minimize salt stress, the way of putting off the ions or impairing the uptake is very complex. However, true halophytes are developed with well-developed transport system that can enable a lower uptake and accumulation of salts in the upper parts of the plant, especially in the transpiring organs, especially leaves (Dajic 2006).

Exclusion of Na^+ happens mainly due to low net Na^+ uptake by cells in the root cortex and the tight control of net loading of the xylem by parenchyma cells in the stele (Davenport et al. 2005). Lower permeability of root even under excessive concentration of soil salinity also actively helps in salt exclusion (Flowers and Hajibagheri 2001; Zhu 2001). The capacity of salt exclusion is, however, directed by several factors like selectivity of uptake by root cells; preferential loading of K^+ rather than Na^+ into the xylem by the cells of the stele; removal of salts from the xylem in the upper parts of roots, the stem, and leaf sheaths, based upon exchange of K^+ for Na^+; and loading of the phloem (Munns 2002). The capacity of plant to sense Na^+ is also an important factor which is extracellularly done by a membrane receptor, whereas intracellular Na^+ may be sensed either by membrane proteins or by any of the many Na^+-sensitive enzymes in the cytoplasm (Carillo et al. 2011).

Among several special characteristics related to the physiological adaptation of halophytes, salt excretion is one of the most efficient mechanisms that prevent excessive concentrations of salts building up in photosynthetic tissues (Hasanuzzaman et al. 2013). Some of the halophytes possess multicellular salt glands and salt hairs; those are common in many halophytes such as *Cressa* (Convolvulaceae); *Frankenia* (Frankeniaceae); *Spartina*, *Chloris*, and *Aeluropus* (Poaceae); *Atriplex* (Chenopodiaceae); *Statice*, *Limonium*, *Plumbago*, and *Armeria* (Plumbaginaceae); *Glaux* (Primulaceae); *Tamarix* and *Reamuria* (Tamaricaceae); and some mangrove species, for example, *Avicennia*, *Aegialitis*, *Aegiceras*, and *Acanthus*. These glands are composed of a set of epidermal cell complexes, those capture salt from the mesophyll cells beneath them, to which they are connected by numerous plasmodesmata, and secrete it at the leaf surface, where a layer of salt crystals is formed (Hasanuzzaman et al. 2013; Fig. 6). The process of salt excretion by salt gland is yet to be elucidated by some researchers; however, one of the requisites is the availability of energy (ATP) which is required for ion pumping. In halophytes, this energy is provided by the active respiration of the glandular cells (Marcum and Murdoch 1992).

Accumulation of compatible solutes is often regarded as basic strategy for the protection and survival of halophytes under salt stress (Lee et al. 2008). These soluble compounds, including soluble carbohydrates, glycine betaine, polyols, and proline (Parida and Das 2005), protect plants against stress by cellular osmotic adjustment, detoxification of reactive oxygen species (ROS) protection of membrane integrity, and stabilization of enzymes and proteins (Ashraf and Foolad 2007).

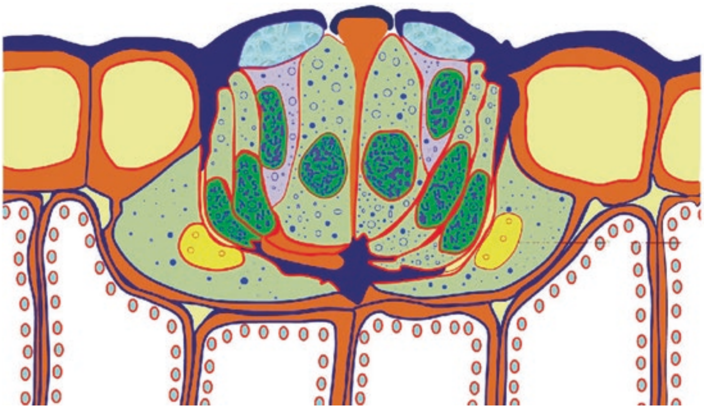

Fig. 6 Cross section of a salt gland (Hasanuzzaman et al. 2013)

Moreover, the leaf tissues of halophytes are adapted to accumulate large amounts of salt ions. Such adaptive mechanism is crucial to generate a water potential gradient along root-shoot to maintain water flux throughout plants (Silveira et al. 2009).

The published literature indicated that the higher the initial EC_e value, the higher the difference between initial and final EC_e values. This can be seen for *Leptochloa fusca*, *Sesbania aculeata*, and *Sesuvium portulacastrum* studies from different sources (Qadir et al. 1997, 2002). A direct comparison of phytoremediation with chemical amendments, namely, gypsum, shows that EC_e reduction does not appear to be markedly different between different treatments, regardless of remediation time. Both treatment types experienced a significant reduction of treatment rates for this parameter by the second year (Qadir et al. 1997) and with lower initial EC_e (Qadir et al. 2002), indicating that treatment efficiency is dependent, once again, on initial contaminant values. Furthermore, the final three tests conducted in non-leaching conditions indicated the possibility of plant uptake as the most significant driving force for remediation. Ravindran et al. (2007) reported that the halophytes could decrease EC_e and SAR values from the above-recommended values for soil (EC_e >4 $dS.m^{-1}$ and SAR >13) to values that may be considered nonsaline or sodic (Fig. 7). The highest reduction in SAR was obtained with *Suaeda maritima.* The reduction in SAR was dramatically decreased at 60th day onwards.

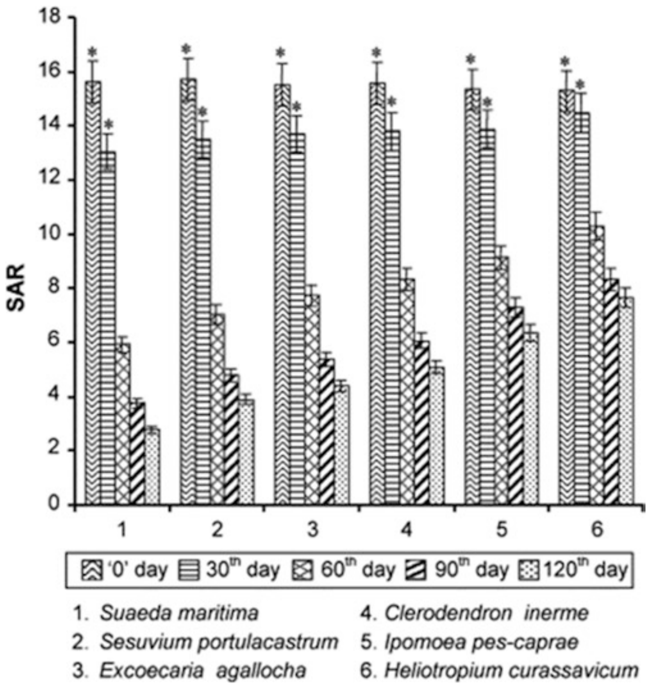

Fig. 7 Effect of six halophytes on reduction of sodium adsorption ratio (SAR) in natural saline soil. Values shown are mean ± SD for five replicate experiments. *significant at 5 % level (from Ravindran et al. 2007)

The application of non-leaching conditions provides further information on salt uptake capacity of plants in soils. Rabhi et al. (2009) reported that in the field, *Suaeda fruticosa* contributed to desalination of the surrounding rhizosphere mostly by improved leaching due to enhancement of soil structure, while the contribution of *Arthrocnemum indicum* was by salt uptake. When both plants were tested in non-leaching conditions, the maximum salt uptake of *S. fruticosa* was in fact higher. It is possible, therefore, that *S. fruticosa* improves the structure of the soil in a more efficient way than *A. indicum*, possibly due to different root systems, and in such a way that leaching occurs too quickly to enable significant amounts of salt uptake. The cultivation of obligate halophyte like *Sesuvium portulacastrum* L. could be a suitable candidate for phytodesalination programs. The cultivation of the halophyte on the salinized soil (phytodesalination culture) led to a marked absorption of Na^+ ions by *S. portulacastrum* roots and their accumulation in the above-ground biomass up to 872 mg plant^{-1} and 4.36 g pot^{-1} (about 1 t ha^{-1}) (Rabhi et al. 2010). The decrease in salinity and sodicity of the phytodesalinized soil significantly reduced the negative effects on growth of the test culture of *Hordeum vulgare*. Its highest phytodesalination capacities can be obtained if defoliation is performed in the beginning of each winter to avoid shedding of Na^+-charged leaves. Harvested shoots can serve for several uses such as fodder (Ramani et al. 2006; Lokhande et al. 2009) and essential oil source (Magwa et al. 2006).

6.3 Advantages of Microbially Enhanced Phytoextraction

- Biological, "green" approach to soil cleanup.
- Contaminant permanently removed from soil.
- Amount of waste material that must be disposed of is decreased up to 95 %.
- Soil retains its structure and microbiological activity.
- It can clean up the soil without causing any kind of harm to soil quality.

6.4 Disadvantages of Microbially Enhanced Phytoextraction

- Only effective within the rhizosphere zone.
- Slow compared with physicochemical techniques.
- Specialized harvesting techniques required.
- Disposal problems for metal-enriched biomass.

7 Conclusion

Phytoremediation, the green cure technology, is an emerging area of research and development for reclamation of either heavy metal- or salt-affected soils. Among various approaches of phytoremediation, phytoextraction is appealing for decontamination of metal- and salt-affected soils. The choice of appropriate phytoremediation plants, soil fertilization, and use of soil amendments including chelating agents determine largely the success of phytoremediation process. A lot of research has already been initiated that is aimed at increasing the bioavailability of metals through chemical amendment. As chemical amendment is a costly input, the thrust of research should be to look for other economically efficient and locally available organic amendments. Very less research has been conducted in the areas of co-contamination with organic and inorganic pollutants with viable bioremediation technology. Identification of efficient microbes and their potential use in the rhizosphere of phytoremediating plants could further enhance the phytoextraction process of contaminants. The main mechanism behind salt phytoremediation has yet to be settled and requires a more focused research effort to assess the contribution of phytoextraction to the remedial process. The phytoremediation, and particularly phytoextraction, unfolded many new opportunities to increase the efficiency and quality of the treatment of salt-affected soils (combination of treatment types, mixed plant cultures, biostimulation, etc.) Nevertheless, these novel applications are still in their infancy and further development is essential.

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Bioremediation of Heavy Metals by Microbes

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1 Introduction

The word "bioremediation" is derived from two words, viz., "bio" which means biological and "remediation" that means to remedy. It is defined as any process that involves microorganisms or their enzymes to remove contaminants from a polluted site. In bioremediation process, mainly microorganisms, such as fungi or bacteria, are used to clean up contaminated soil and water (Strong and Burgess 2008; Kumar et al. 2011). It encompasses many technologies and practices that make use of natural systems and processes to remove pollutants from contaminated sites. Many microorganisms that reside in soil and water naturally consume certain chemicals that may cause harm to human beings as well as the environment. At present, bioremediation is the most effective management system that can deal with polluted environment and recover contaminated sites (Ahemad and Khan 2011). Stimulation of bioremediation activity through microorganisms can be achieved by supplementing nutrients (nitrogen and phosphorus), electron acceptors (oxygen), and substrates (methane, phenol, and toluene) or by introducing new microorganisms having desired catalytic capabilities (Ma et al. 2007; Baldwin et al. 2008). Bioremediation

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technology is normally targeted to remove heavy metals, radionuclides, organic waste, pesticides, etc., from polluted sites or industrial discharges through biological means. It is of relatively low cost, of low technology, and with high public acceptance and can often be carried out on site. The result of remediation depends upon type of contaminants, time duration, and methodology.

2 History

Bioremediation offers the possibility to destroy, alter, or render various contaminants through utilization of natural biological activities. It is one of the world's oldest and yet newest pollution-fighting tools. There has been evidence that in 6000 BC also compost piles existed and in 1891 the first biological sewage treatment plant was established in Sussex, UK. These are the types of bioremediation. In 1972, the first commercial use of a bioremediation system was started to clean up a Sun Oil pipeline spill in Ambler, Pennsylvania (National Research Council 1993). Bioremediation is proving effective in treating hazardous materials ranging from toxic chemicals and heavy metals to oil and nuclear waste. Volesky (1990) first observed capabilities of some fungi to accumulate metallic elements inside their cells. The Environmental Protection Agency in 1992 made a survey in the United States and reported 240 cases of bioremediation (Alexander 1999) where treatments of contaminated soil or groundwater were most common.

3 Pollution by Heavy Metals

Different types of inorganic and organic pollutants are heavily loaded in industrial wastewater which is normally discharged in water bodies (Ng and Tjan 2006). Unscientific discharges of these huge quantities of wastewater loaded with heavy metals cause not only environmental and human health problem due to their toxicity (Diels et al. 2002; Gikas 2008), but the cost of wastewater treatment was also increased (Fatta-Kassinos et al. 2011; Madoni et al. 1996). Heavy metals are not biodegradable with higher persistence in wastewater treatment, and their toxicity, particularly in high concentrations, has become a serious global issue (Ng and Tjan 2006). The pollutants are lead, chromium, cadmium, mercury, uranium, selenium, zinc, arsenic, gold, silver, copper, and nickel. These toxic substances are normally produced from mining operations, refining ores, sludge disposal, paints, alloys, batteries, fly ash from incinerators, processing of radioactive materials, metal plating, or the manufacture of electrical equipment, pesticides, or preservatives. Heavy metals such as zinc, lead, and chromium have many uses in basic engineering works, organo-chemicals, petrochemicals, paper and pulp industries, leather tanning, fertilizers, etc. Automobiles and battery manufacturers cause major lead pollution. Fertilizer and leather tanning industries are the source of zinc and chromium, respectively. Industry is not only the sole contributor of these toxic metals; heavy metals can sometimes come into the environment through natural processes also. For example, in many parts of the globe, arsenic in naturally occurring geologic deposits can dissolve into groundwater resulting in unsafe levels in drinking water supplies in the area. After release to the environment, these toxic metals can remain as such for decades or centuries, leading to increase the possibility of human exposure. In addition to drinking water, air pollutants, contaminated soils or industrial waste, and consumption of food produced from polluted soils are also sources of heavy metal exposure. Mineral rock weathering and anthropogenic activities are the two main sources of metal inputs to soils. Interestingly, in our environment and diet, small amounts of these elements are mostly present and actually necessary for good health, but acute or chronic toxicity may happen with higher amounts of any of them. Heavy metals are harmful because they have a tendency to bioaccumulate and cause several health problems in living beings. Neurotoxic, nephrotoxic, fetotoxic, and teratogenic effects are generally observed in heavy metal (HM) toxicity. The toxin itself and the individual's degree of exposure to the toxin decide the level to which a system, organ, tissue, or cell is affected by a heavy metal toxin. Toxic levels can be just above the normal concentrations naturally found in nature for some heavy metals. Therefore, it is vital for us to update ourselves about the harmful effect of heavy metals and precautionary measures against excessive exposure. The health problems due to exposure of heavy metals in human beings are listed below (Table 1):

As the body systems in the fetus and infants develop very fast, young children are more sensitive to the toxic effects of heavy metals. Learning difficulties, memory impairment, damage to the nervous system, and behavioral problems such as aggressiveness and hyperactivity can happen due to childhood exposure to some metals. Irreversible brain damage can occur at higher doses of heavy metals.

Table 1 Adverse effects of heavy metals on humans

Heavy metals	Adverse effects
Lead (Pb)	Acute or chronic damage to the nervous system under long term exposure
Cadmium (Cd)	Renal dysfunction, lung disease, lung cancer and damage to respiratory systems
Copper (Cu)	Anemia at high dose, liver and kidney damage, stomach and intestinal irritation
Mercury (Hg)	Blindness and deafness, brain damage, digestive problems, kidney damage, lack of coordination and mental retardation
Chromium (Cr)	Irritation of skin and ulceration at low-level exposure. Kidney and liver damage and damage to circulatory and nerve tissues at long-term exposure
Arsenic (As)	Sensory changes, numbness, tingling and muscle tenderness, neuropathy, hyperpigmentation, hyperkeratosis and cancer
Nickel (Ni)	Skin cancer, asthma, bronchial cancer

4 Different Methods of Heavy Metals Removal

Chemical precipitation, adsorption, coagulation, ion exchange, electrodialysis, cementation, electrowinning, electrocoagulation, and reverse osmosis are some of the conventional methods used for removing metals from aqueous solutions.

4.1 Precipitation

The most common method followed for removing toxic heavy metals from water up to parts per million (ppm) levels is precipitation. It uses the principle of precipitation some metal salts which are insoluble in water and get precipitated when the correct anion is added. Low pH and the presence of other salts (ions) affect its efficiency. Addition of other chemicals is required under this process leading to the generation of high water content sludge. But the disposal of the precipitated material is a costly affair (Gray 1999).

4.2 Ion Exchange

In industry, for the removal of heavy metals from effluents, this method is used successfully. This method can achieve parts per billion (ppb) level of cleanup while managing relatively large volume of contaminants though it is relatively costly as compared to the other methods. An ion exchanger is a solid capable of exchanging either cations or anions from the surrounding materials. Synthetic organic ion exchange resins are commonly used matrices for this method. The method has disadvantage over others that it cannot handle concentrated metal solution as the matrix gets easily fouled by organics and other solids in the wastewater. Moreover, this method is nonselective and is highly dependent on pH of the solution.

4.3 Electrowinning

In mining and metallurgical industrial operations, this method is widely used for heap leaching and acid mine drainage. In metal transformation, electronics, and electrical industries, it is also used for removal and recovery of metals.

4.4 Electrocoagulation

An electric current is used in this method for removing metals from solution. Electrocoagulation system is also useful in cleaning suspended solids, dissolved metals, tannins, and dyes. Electrical charges maintained the contaminants present in wastewater in solution. After neutralization of these ions and other charged particles with ions of opposite electrical charges supplied by this method, contaminants become destabilized and precipitate in a stable form.

4.5 Cementation

Cementation is also another type of precipitation method. It is an electrochemical mechanism where a metal with higher oxidation potential passes into solution, e.g., oxidation of metallic iron, Fe (0), to ferrous iron (II), and replaces a metal having a lower oxidation potential. By using cementation method, copper is most frequently separated along with other metals such as Ag, Au, and Pb, and also As, Cd, Ga, Pb, Sb, and Sn can be recovered in this manner.

4.6 Reverse Osmosis

Semipermeable membranes are used in this method for the recovery of metal ions from dilute wastewater.

4.7 Electrodialysis

In this method, between the electrodes in electrolytic cells, selective membranes (alternation of cation and anion membranes) are fitted. There is migration of ions under continuous electrical current leading to the recovery of metals.

However, when the concentration of metal ion in aqueous solution is in between 1 and 100 mg L^{-1}, chemical precipitation and electrochemical treatment are unsuccessful. The processes such as ion exchange, membrane technologies, and activated carbon adsorption process are very costly while managing large amount of water and wastewater containing heavy metals in low concentration prohibiting their large-scale use. Conventional treatment technologies have another major disadvantage, i.e., the production of toxic chemical sludge as well as its expensive disposal and non-eco-friendly nature. Volesky (2001) summarized the advantages and disadvantages of those conventional metal removal technologies. The development of safe and cost-effective alternative approaches for dealing with wastes is encouraged/promoted due to growing public awareness and concern about environmental pollutants. Bioremediation has emerged as the most promising approach for cleaning up many environmental pollutants among all the technologies that have been studied.

5 Types of Bioremediation

Generally, bioremediation technologies are classified as:

1. In situ (at the site of contamination)
2. Ex situ (contaminant taken out of the site of contamination and treated elsewhere).

Because of cost-effectiveness and less disturbances through avoiding excavation and transport of contaminants, in situ method is generally the most desirable method. It involves supplying oxygen and nutrients by circulating aqueous solutions through contaminated soils for stimulation of naturally occurring bacteria to degrade organic contaminants. Generally this method can be used for cleaning up contaminated soil and groundwater. For in situ bioremediation to be successful, four main requirements are very much important. These are:

(a) Presence of sufficient microorganisms to bioremediate the contaminants
(b) Availability of required nutrients
(c) Good environmental conditions
(d) Sufficient time to allow the natural process to degrade the contaminant

Methods of in situ bioremediation are mentioned below.

5.1 Bioaugmentation

In bioremediation process, indigenous or exogenous microorganisms are frequently added to the contaminated sites in order to reinforce the natural biological processes. In this method, specific competent strains or consortia of microorganisms are introduced to improve the degradative capacity of contaminated areas. Bioaugmentation method is more commonly and successfully used on contaminants removed from the original site, such as in municipal wastewater treatment facilities. Bioaugmentation is used at sites where soil and groundwater are contaminated with chlorinated ethenes, such as tetrachloroethylene and trichloroethylene, to ensure that the in situ microorganisms can completely degrade these contaminants to nontoxic ethylene and chloride. In bioaugmentation process both single strains as well as consortia can be used. For this purpose microorganisms may be isolated from contaminated soils, and after culturing under laboratory conditions, the pure bacterial strains are returned to the same soil. However, in removing pollutants, the use of consortia of aromatic-degrading bacteria has been found to be more effective as compared with selected single strains (Ghazali et al. 2004; Goux et al. 2003). There is difficulty in monitoring of this system. When immediate site cleanup is required, it is not the best approach as the in situ process is slow.

5.2 Biopiling

In this method contaminated soils are excavated and mixed with soil amendments and then placed on a treatment area where bioremediation was done using forced aeration. Carbon dioxide and water are produced after the contaminants are reduced. A treatment bed, an aeration system, an irrigation/nutrient system, and a leachate collection system are required for a basic biopile system. For enhancing biodegradation process, moisture, heat, nutrients, oxygen, and pH are controlled.

5.3 Biosparging

For increasing groundwater oxygen concentrations and hastening the rate of biological degradation of contaminants by indigenous microorganisms, injection of air under pressure below the water table is done in this method. It increases the contact between soil and groundwater through mixing in the saturated zone. This method can be used to reduce petroleum constituents that are adsorbed to soil within the capillary fringe, below the water table or dissolved in groundwater. Biosparging is commonly used at sites with mid-weight petroleum products such as diesel fuel; lighter petroleum products tend to volatilize swiftly and are removed very rapidly through sparging. The most important factor responsible for effectiveness of this technology is soil permeability.

5.4 Bioventing

The most common in situ treatment method is bioventing which involves air and nutrient supply through wells to contaminated soil for stimulation of the indigenous bacteria. Here low airflow rate provides only the amount of oxygen necessary for the biodegradation while minimizing volatilization and release of contaminants to the atmosphere. It works for simple hydrocarbons and can be used where the contamination is under the deep surface.

Ex situ strategies separate contaminants and place them in a contained environment. For easier monitoring and maintaining of conditions and making the actual bioremediation process faster, these contaminated materials should be kept in a contained environment. However, the removal of the contaminants from the contaminated site is time-consuming, costly, and potentially dangerous. By bringing the contaminants to the surface, there would be increased exposure to the toxic materials to human beings. The methods of ex situ bioremediation process are as follows.

5.5 Landfarming

In this method, excavation of contaminated soil is done, and after that the soil is spread over a prepared bed and periodically tilled until degradation of most of the pollutants is achieved. Stimulation of the indigenous biodegradative microorganisms and facilitating their aerobic degradation of contaminants are the main objective of this method. Landfarming method has received much attention as a disposal way due to its potential to reduce monitoring and maintenance costs as well as cleanup liabilities.

5.6 Composting

Here contaminated soil is combined with nonhazardous organic amendments such as manure or agricultural wastes and composted. As a result rich microbial population is developed in the presence of these organic materials, and elevated temperature during composting transforms degradable organic waste into humus-like substance.

5.7 Bioreactors

Any device or system that supports a biologically active environment is called a bioreactor. For ex situ treatment of contaminated soil and water from a contaminated plume, slurry reactors or aqueous reactors are used. Bioremediation in this method involves the processing of contaminated solid material (soil, sediment, sludge) or water through an engineered containment system.

For developing an effective waste cleanup of contaminants in soils and water, combination of the abovementioned bioremediation methods in different ways or integrated with other strategies such as chemical or physical remediation technologies can be followed.

6 Heavy Metal Removal by Microorganisms

In this decade, the research interest has been on the use of biomass of fungi, algae, and bacteria as an absorbent material to remove heavy metals. Renewable biomass of various microorganisms may prove an environment friendly alternate to physicochemical remediation processes and will be considered for its ability to serve as biotrap for heavy metals. Biotraps are any organisms (living or nonliving) or component of organism which can bind with or alter the form of a toxic metal and allowing its removal and recovery from polluted water or soil or rendering it harmless (Crusberg and Mark 2000). The use of microbial adsorbents such as bacteria, fungi, algae, and some agricultural wastes that emerged as an eco-friendly and effective

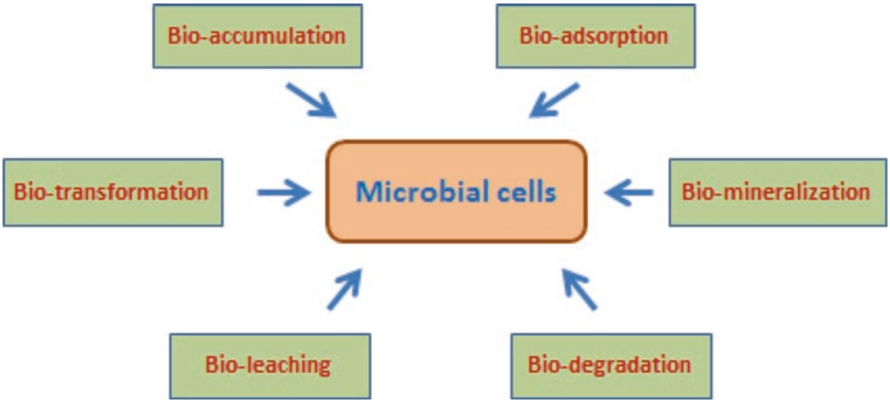

Fig. 1 Metal-microbe interactions in bioremediation

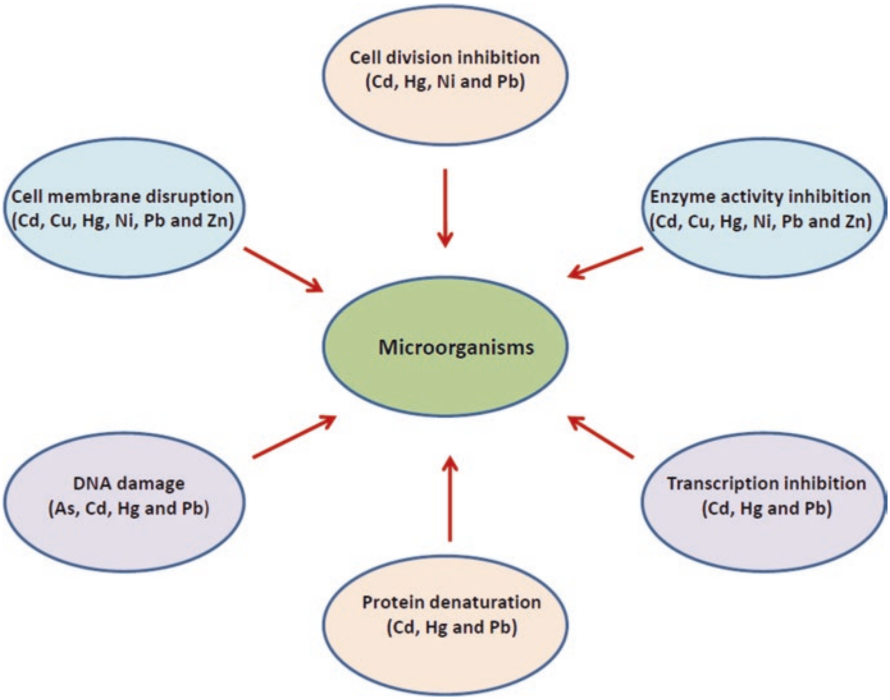

Fig. 2 Mechanisms of heavy metal-toxicity to microbes. Modified from Rajendran et al. (2003)

material option could offer potential inexpensive alternatives to the conventional adsorbents (Valls and De Lorenzo 2002). There are several mechanisms of bioremediation as biosorption, metal-microbe interactions, bioaccumulation, biomineralization, biotransformation, and bioleaching (Figs. 1 and 2). Microorganisms remove the heavy metals from soil by using chemicals for their growth and development.

The response of microorganisms toward toxic heavy metals is very important for reclamation of polluted sites (Congeevaram et al. 2007). Microorganism requires the optimum temperature, nutrients, and amount of oxygen for their growth. Physiology of microbes is affected by heavy metals in several ways (Fig. 1), but many of them survived under theses stresses. Bacteria have evolved several mechanisms for their survival under metal-stressed environment, by which they can immobilize, mobilize, or transform metals rendering them inactive to tolerate the uptake of heavy metal ions (Nies 1999). These mechanisms include exclusion (the metal ions are kept away from the target sites), extrusion (the metals are pushed out of the cell through chromosomal-/plasmid-mediated events), accommodation (metals form complex with the metal-binding proteins, e.g., metallothioneins, low molecular weight proteins) (Kao et al. 2006; Umrania 2006) or other cell components, biotransformation (toxic metal is reduced to less toxic forms), and methylation-demethylation. These mechanisms allow microorganisms to function metabolically in metal-contaminated environment. These mechanisms could be constitutive or inducible. It is probably that bacteria acquire their resistance to heavy metals by gene transfer or spontaneous mutation on plasmids and transposons. For example, in Gram-negative bacteria (e.g., *Ralstonia eutropha*), the czc system is responsible for the resistance to cadmium, zinc, and cobalt. The czc genes encode for a cation-proton antiporter (CzcABC), which exports these metals (Nies and Silver 1995). A number of bacteria and fungi are used for heavy metal removal having different mechanisms as described below.

6.1 Bacteria Used for Heavy Metal Removal

Till date, many researchers have done work on different bacterial species for their bioremediation potential; some of them are listed in Table 2. The major mechanism that involved inbacterial resistance to heavy metals is through efflux transporters. The efflux of heavy metals is primarily facilitated by P-type ATPases, CBA transporters, and CDF chemiosmotic transporters.

6.1.1 Efflux Transporters

Three major families of efflux transporters are involved in heavy metal resistance. CBA transporters are three-component transmembrane pumps of Gram-negative bacteria which comprise of an RND (resistance, nodulation, and cell division) protein, an MFP (membrane fusion protein) protein, and an OMF (outer membrane factor) (Franke et al. 2003). Another type of transporters belongs to P-type ATPases which span the inner membrane and use ATP energy to pump metal ions from the cytoplasm to periplasm. Cation diffusion facilitator (CDF) family of transporters acts as chemiosmotic ion-proton exchangers (Anton et al. 1999; Grass et al. 2001). In general, P-type ATPases and CDF transporters are commonly found among

Table 2 Bacterial species employed in the bioremediation of heavy metals

Bacteria	Heavy metal	Adsorption capacity (mg/g)	References
Acinetobacter sp.	Zn	36	Tabaraki et al. (2013)
Bacillus sp.	Pb	92.3	Tunali et al. (2006)
Bacillus firmus	Pb	467	Salehizadeh and Shojaosadati (2003)
Corynebacterium glutamicum	Pb	567.7	Choi and Yun (2004)
Desulfovibrio desulfuricans	Cd, Ni, Cr	99.9, 98.3, 74.2 %	ock Joo et al. (2015)
Enterobacter cloacae	Pb, Cd, Ni	171.8, 114.2, 32.2	Banerjee et al. (2015)
Pseudomonas aeruginosa	Pb	46.1	Ahmady-Asbchin et al. (2015)
Pseudomonas putida	Pb	270.4	Uslu and Tanyol (2006)
Streptomyces rimosus	Zn	30	Mameri et al. (1999)
Aphanothece halophytica	Zn	133.0	Incharoensakdi and Kitjaharn (2002)
Thiobacillus ferrooxidans	Zn	172.4	Liu et al. (2004)
Bacillus subtilis	Cu	20.8	Nakajima et al. (2001)
Micrococcus luteus	Cu	33.5	Nakajima et al. (2001)
Enterobacter sp.	Cu	275	Bestawy et al. (2010)
Pseudomonas cepacia	Cu	65.3	Savvaidis et al. (2003)
Pseudomonas stutzeri	Cu	22.9	Nakajima et al. (2001)
Sphaerotilus natans	Cu	60	Beolchini et al. (2006)
Kocuria flava	Cu	90 %	Achal et al. (2011)
Stenotrophomonas sp.	Cu	–	Zaki and Farag (2010)
Zoogloea ramigera	Cr	2	Nourbakhsh et al. (1994)
Ochrobactrum anthropi	Cd	–	Ozdemir et al. (2003)
Sphingomonas paucimobilis	Cd	–	Tangaromsuk et al. (2003)
Stenotrophomonas sp.	Cd	320	Bestawy et al. (2010)

different bacterial species, whereas the presence of a CBA transporter (an RND protein in Gram-positive bacteria) is exceptional and indicates high level of resistance to heavy metal ions (Nies 2003).

Some of these efflux systems are general in the sense that they confer resistance to a number of similar metal ions such as Zn^{2+}, Co^{2+}, Cu^{2+}, and Pb^{2+}, while some are extremely specific like *pbrTRABCD* which only transports Pb^{2+} ions. Several Zn^{2+}/Cd^{2+} efflux ATPases are known to transport Pb^{2+} also. *zntA* from *E. coli*, *cadA* from *S. aureus*, *PbrA* from *Cupriavidus metallidurans CH34*, and *cadA2* from *P. putida* have been shown to effectively transport Pb^{2+}, Zn^{2+}, and Cd^{2+} (Marchler-Bauer et al. 2007). A CBA transporter, *CzcCBA1*, from *Pseudomonas putida KT2440* has only been recognized to take part in export of Pb^{2+} from the cell, while no transporters from the CDF family have yet been found to have such activity (Hynninen et al. 2010). *pbrD* is a protein involved in Pb^{2+} sequestration, while *pbrR* protein mediates Pb^{2+} inducible transcription from its divergent promoter, regulating the pbr operon

(Borremans et al. 2001). Bacterial resistance to nickel is due to the *nikABCDER* operon. Among these *NikR* encodes for a Ni-binding protein, *NikABCD* encodes for an ATP-dependent transport system (Navarro et al. 1993) and *nikE* hydrolyze ATP and couple this energy to Ni transport. Another transport system *abcABCD* has been found in organism like *H. pylori* conferring resistance to Ni (Hendricks and Mobley 1997). A Ni/Co ABC-type transporter was also found in *Actinobacillus pleuropneumoniae* where a five-gene operon, *cbiKCMQO*, displays sequence homology to component of other known ATP-dependent transporters and was responsible for tolerance to Ni and Co (Bossé et al. 2001). Y*ersinia pseudotuberculosis*, *Y. pestis*, and *Y. enterocolitica* posses both *yntABCDE*ABC-type transporters and *ureH*-type permeases responsible for Ni uptake and transport into the cell.

In *Pseudomonas syringae* Cu^{2+} resistance was due to four copper proteins Cop A, B, C, and D encoded by *Cop* operon present on bacterial plasmid which compartmentalize Cu^{2+} (Cooksey 1993; Cooksey 1994; Spain and Alm 2003). However, *E. coli* implies a different mechanism to counter high Cu^{2+} concentration via efflux mechanisms. The efflux proteins are expressed by plasma-borne *pco* genes, which are dependent upon expression by chromosomal *cut* genes (Cooksey 1993). *Cut C* and *cut F* encode a copper-binding protein and outer membrane lipoprotein (Gupta et al. 1995). In *E. coli* the *cueO* multi-copper oxidase and *cusCFBA* multicomponent efflux transport system prevent cell against Cu^{2+} (Singh et al. 2004; Franke et al. 2003; Rensing and Grass 2003). *CusCBFA* is an RND efflux chemiosmotic carrier responsible for copper transport (Franke et al. 2003). In *R. metallidurans* Cr3Y PCoA*,* PCoA*,* and PCoC are periplasmic protein-binding copper responsible for resistance to copper (Cavet et al. 2003).

ZntA, a zinc-transporting P-type efflux ATPase, is found in *E. coli* and *R. metallidurans* (Blencowe and Morby 2003). Another transporter belonging to RND family, zntCBA, has also been reported to efflux Zn^{2+} in cyanobacteria (Cavet et al. 2003). In *E. coli Zit B* and *CZCD* in *R. metallidurans* are chemiosmotic Zn^{2+} transporters of the cation diffusion facilitator (CDF) protein family maintaining Zn^{2+} homeostasis and resistance in bacterial cells (Nies 2003).

In some cases of Gram-negative bacteria, transport of mercury across the membrane is mediated by MerE and MerGin (Sone et al. 2010). Once inside the cytoplasm, *merB*-encoded enzyme organomercurial lyase cleaves the C-Hg bond, thereby releasing Hg^{2+}. Hg^{2+} is then subsequently reduced to Hg^0 by merA-encoded enzyme mercuric ion reductase. Mercury resistance is also conferred by a +ve regulated operon which may be located on plasmid (Schelert et al. 2004), on genomic DNA, on integrons (Wireman et al. 1997), or on a component of Tn21 transposon. Mer operon consists of functional genes such as *merP*, *merT*, *merD*, *merA*, *merF*, *merC*, and *merB* and a regulatory gene *merR* transcripted separately. *merA* codes for mercuric ion reductase and *merB* codes for mercurial lyase. Two other genes *merG*, a phenylmercury efflux protein, and *mere*, methylmercury-transporting protein, have also been reported to be efficient in conferring resistance against mercury (Sone et al. 2010).

Various bacterial strains conferring resistance to Cr (V1) such as *E. coli*, *P. putida*, *Desulfovibrio*, *Bacillus* sp., *Shewanella* sp., *Arthrobacter* sp., *Streptomyces* sp. MC1, and *Mycobacterium* sp. CR-07 have been reported (Peitzsch et al. 1998; Morais et al. 2011). The mechanism of resistance in these bacteria is due to *chrB-CAF* operon from transportable elements, where *chrA* and *chrB* proteins act as chromate-sensitive regulator. In *P. putida MK1*, a soluble reductase chrR, was purified which reduces Cr (V1) to a less toxic form Cr III, while in *E. coli* reductase YieF was found to be responsible for conversion of Cr (V1) to Cr (III). In case of cadmium, *SmtA*, a metallothionein from *Synechococcus PCC7942*, sequesters and detoxifies Zn^{2+} and Cd^{2+}. *C metallidurans CH34* has four Zn^{2+}/Cd^{2+} transcolating P-type ATPase for $Zn^{2+}/Cd^{2+}/Co^{2+}$ export (Scherer and Nies 2009). *czcD*a CDF transporter is also responsible for Zn^{2+} and Cd^{2+} resistance (Anton et al 1999). The czcCBA complex from *C. metallidurans* is a type of CBA transporter-encoding protein showing resistance to Cd^{2+}, Zn^{2+}, and Co^{2+} by metal efflux as in *P. aeruginosa*, *P. putida*, and *Alcaligenes* spp. (Hu and Zhao 2007). A plasmid-borne *CadA* gene encodes a cadmium-specific ATPase in several bacterial genera including *Pseudomonas*, *Bacillus*, and *E. coli.* Schmid and Schlegel (1994) reported that the *czc* and *ncc* operons are also responsible for cadmium resistance in *Alcaligenes eutrophus* and *Alcaligenes xylosoxidans*, respectively. *CadA* is responsible for the removal of Cd^{2+} in *P. putida. ZntA* from *E. coli* and *CadA* from *Staphylococcus aureus* show translocation of $Zn^{2+}/Cd^{2+}/Pb^{2+}$ across the membrane (Nucifora et al. 1989).

Ars operon has been a sole player in mediating arsenic resistance in bacteria. A three-gene operon *arsRBC* present in *E. coli* genome and on *Staphylococcus aureus* plasmid pl258 was found responsible for Ars resistance (Lebrun et al. 2003; Silver and Phung 2005). *ArsRDABC* on *E. coli* plasmid R773 provides resistance to high concentration of arsenic. *T. arsenitoxidans3A* has both operons. In addition to these operon genes *arsH, arsN*, *and Acr 3p* (Achour et al. 2007), *Aqp S*, an aquaglyceroporin, was also found to be responsible for arsenite resistance (Yang et al. 2005). A putative membrane permease *arsP* from *Campylobacter jejuni*, *arsTX* encoding a thioreductase system in *Microbacterium* sp. *A33*, and *arsN* have also been found in ars operon with suggested role in arsenic resistance (Achour-Rokbani et al. 2010; Chauhan et al. 2009). *arsM*, an arsenic methyl transferase gene from *Rhodopseudomonas palustris*, also has a role in arsenic resistance.

6.1.2 Binding by Siderophores

Microorganisms secrete a wide array of iron-chelating compounds termed as siderophores; these siderophores not only have a high affinity for iron but also bind other metal ions outside the cell (Saha et al. 2013; Schalk et al. 2011). *Pseudomonas* species particularly *Pseudomonas aeruginosa 4EA* and *Pseudomonas putida KNP9* produce a characteristic yellow-green siderophore belonging to the class pyoverdines. These siderophores produced by bacterial strains *Pseudomonas aeruginosa 4EA* and *Pseudomonas putida KNP9* were used in complexation of Pb(II) (Naik and Dubey 2011; Tripathi et al. 2005). It was found that there was a reduction of 93 % of Pb(II) in mung bean roots and 56 % in mung bean shoots (Tripathi et al. 2005).

In *P. aeruginosa PAO1*, pyochelin has been associated with binding of Pb(II) and Ni(II). Another siderophore from the same bacteria pyoverdine has also been associated with the binding of both Pb^{2+} and Ni^{2+} ions. However the binding of Pb by pyochelin was stronger as compared to pyoverdine (Braud et al. 2010).

6.1.3 Binding by Specific Proteins

Metallothioneins (MTs) is a name given to a family of cysteine-rich metal-binding proteins found in bacteria, fungi, plants, as well as animals. MTs have been found to bind both essential as well as nonessential heavy metals. In a study Murthy et al. (2013) isolated a metallothionein protein capable of binding Pb. It was found that there was an increase in the metallothionein biosynthesis in *B. cereus* when it was exposed to increased Pb concentrations up to 500 mg/l. Metallothioneins (MTs) are proteins that protect cells from toxic metals; however, their main function is in homeostasis of zinc (Blindauer 2011). MTs, first discovered in *Synechococcus PCC 7942*, are encoded by the smt locus, which consists of two divergently transcribed genes *smtA* and *smtB*. Class II MT is encoded by *smtA*, and the transcription of *smtA* is repressed by product of *smtB*. SmtA is involved in homeostasis of zinc, as its deletion in *Synechococcus PCC 7942* leads to its hypersensitivity to Zn(II) (Blindauer 2011). In addition to Zn(II), Pb(II) is also able to switch on the expression of *smtA*. Apart from *Synechococcus* PCC 7942, *smt* gene induction and biosynthesis of MT in the presence of Pb(II) have been reported in *B. cereus*, *Streptomyces* sp., *Salmonella choleraesuis 4A*, and *Proteus penneri GM-10* (Huckle et al. 1993; Naik et al. 2012; Rifaat et al. 2009). Another gene (*bmtA*) which encodes Pb(II)-binding metallothionein has been detected in *P. aeruginosa WI-1* (Naik et al. 2012). Metallothionein-like protein binds Pb(II) in *Bacillus megaterium* (Roane 1999). Some of the extracellular enzymes, such as superoxide dismutase from *Streptomyces subtilis*, can also be used in binding of Pb(II) (So et al. 2001).

Significant differences ($p<0.05$) were observed by Kamika and Momba (2013) between dead and living microbial cells for metal removal, and the presence of certain metal-resistant genes indicated that the selected microbial isolates used both passive (biosorptive) and active (bioaccumulation) mechanisms to remove heavy metals from industrial wastewater. This study advocates the use of *Peranema* sp. as a potential candidate for the bioremediation of heavy metals in wastewater treatment, in addition to *Pseudomonas putida* and *Bacillus licheniformis.*

Bioremediation depends on the natural biological processes of microorganisms, one of which is metabolism. Metabolism refers to all the chemical reactions that happen in a cell or organism. All living processes are based on a complex series of chemical reactions. Metabolic processes fall into two types—those that build complex molecular structures from simpler molecules, called anabolism, and those that break down complex molecules into simpler molecules, called catabolism. Chemicals present in contaminated sites can be remediated through either, or both, of these processes. Chemicals present at contaminated sites become part of the anabolism and catabolism process. For example, hydrocarbons (part of the carbon family) present at sites with petroleum products can be taken up by microorganisms and used as building blocks for cell components. Other chemicals that are important to a microorganism include chemical compounds in the phosphorus, potassium, calcium, and sodium group. Microorganisms also need trace elements of other chemicals, including chromium, cobalt, copper, and iron, all of which can be available in abundance at contaminated sites.

Metals are not destroyed by microbes. However metal and metalloid containing molecule or ion may be modified, immobilized, or detoxified so that bioremediation may be feasible. Microbes through the process of adsorption remove heavy metals. Most microorganisms possess mechanisms for detoxification of metals. These are exclusion from the cell or from the cytoplasm, incorporation into granules, precipitation within the cell wall, complex with extracellular polymers, and transformation of metals through oxidation reduction.

Mechanisms are involved in the detoxification and transformation of metals, including mechanisms that restrict entry into the cell and intracellular detoxification or organellar compartmentation, the latter occurring in some eukaryotes, e.g., algae and fungi. Operation of a number of mechanisms is possible depending on the organism and the cellular environment; mechanisms may be dependent on and/or independent of metabolism. A variety of mechanisms may be involved in transport phenomena contributing to decreased uptake and/or efflux. A variety of specific or nonspecific mechanisms may also affect redox transformations, intracellular chelation, and intracellular precipitation. Biomineral formation (biomineralization) may be biologically induced, i.e., caused by physicochemical environmental changes mediated by the microbes, or biologically controlled (solid rectangles) (Gadd 2009).

6.2 Fungi Used for Heavy Metal Removal

Many fungal species have been reported such as *Aspergillus niger*, *Trichoderma aureoviride*, *T. harzianum* (Iskandar et al. 2011), *T. virens* (Siddiquee et al. 2013), and *Penicillium* sp.(Martins et al. 2015) that are used in the process of cleaning polluted areas; some are listed in Table 3. The metal resistance in fungi is primarily expressed by two major mechanisms:

1. Extracellular sequestration—it is characterized by chelation and cell-wall binding. Extracellular chelation of metal ions occurs due to the secretion of various extracellular polymeric substances (EPS) by fungi. The effect of EPS on Pb^{2+} removal by a polymorphic fungus *Aureobasidium pullulans* was studied, and it was found that due to the existence of EPS, Pb^{2+} only accumulated on the surface of the intact cells of *A. pullulans*, whereas in EPS-extracted cells of *A. pullulans*, Pb^{2+} penetrated into the inner cellular parts (Suh et al. 1999). The uptake capacity of Pb^{2+} by intact cells depends on the storage of cells. Extracellular cell-wall binding commonly known as biosorption is one of the major mechanism contributing to fungal resistance against heavy metals. Fungal cell wall contains large

Table 3 Fungal spices employed in the bioremediation of heavy metals

Fungi	Heavy metal	Adsorption capacity (mg/g)	References
Aspergillus sp.	Cr, Cd	1.20, 2.72	Zafar et al. (2007)
Aspergillus foetidus	Cr(VI)	2	Prasenjit and Sumathi (2005)
Aspergillus lentulus	Cr, Pb	331, 1120	Mishra and Malik (2012)
Aspergillus niger	Cu(II), Pb(II).	20.91, 54.05	Iskandar et al. (2011)
Aspergillus terreus	Th, U	60, 10	Tsezos and Volesky (1981)
Aureobasidium pullulans	Cu	6	Gadd and Mowll (1985)
Aspergilus versicolor	Cd	7.3	Fazli et al. (2015)
Ganoderm alucidum	Cu	24	Muraleedharan and Venkobachar (1990)
Penicillium chrysogenum	Cd, Cu, Pb	11, 9, 116	Niu et al. (1993)
Pleurotus ostreatus	Pb	165	Zhang et al. (2016)
Pleurotus sapidus	Cd, Hg	127, 287	Yalçinkaya et al. (2006)
Pleurotus mutilus	U	636.9	Mezaguer et al. (2013)
Penicillium spinulosum	Cu, Zn	0.4–2, 0.2	Townsley and Ross (1985)
Phanerochaete chrysosporium	Cd	84.5	Gabriel et al. (1996)
Rhizopus sp.	Cr, Cd	4.33, 2.72	Zafar et al. (2007)
Rhizopus nigricans	Cd, Ni, Pb	19, 5, 166	Fourest and Roux (1992)
Rhizopus oligosporus	Cr	126	Ariff et al. (1999)
Rhizopus arrhizus	Ni, Cd, Zn, Pb, Cu	18, 27, 14, 56, 9.5	Fourest and Roux (1992)
Trametes versicolor	Zn	43.87	Şahan et al. (2015)
Termitomyces clypeatus	Cr	24.84	Fathima et al. (2015)

amounts of polymer of N-acetyl, chitin, and chitosan and deactivated glucosamine on their cell wall which represents a large number of potential binding sites by free hydroxyl, amine, and carboxyl groups. The amine group which contains nitrogen atom has the ability to bind a proton and the hydroxyl group containing oxygen atom may bind to metal ion.

2. Intracellular sequestration—it is the binding of metal to proteins or other ligands to prevent damage to the metal-sensitive cellular targets. In intracellular mechanism, various efflux proteins or metal transport proteins are involved which work by either extruding toxic metal ions from the cytosol out of the cell or by sequestration of metals into vacuolar compartments (Ghazali et al. 2004, Goux et al. 2003). In heavy metal-resistant fungus *Cladosporium cladosporioides*, many intracellular crystals of various sizes were observed in the cytoplasm of the hypha cells grown in a Mn-rich medium. It grew normally in a medium containing 60 mM Mn^{2+} and could endure 1200 mM as the highest concentration tested. Quantification analysis confirmed a high accumulation of Mn which was 58 mg/g in dried biomass. The resistance was also influenced by pH of the medium, which was lost above pH 8 (Shao and Sun 2007).

7 Special Features of Bioremediation

- It is a bio-treatment process for contaminated sites such as water and soil. Microbes can degrade the contaminant and increase their numbers in the presence of contaminant. The biodegradative population declines with the degradation of contaminant. The end products of bioremediation are usually harmless.
- Bioremediation can be done in situ with very less efforts and often without causing a major disruption of normal activities. In situ treatment of contaminants eliminates the need of transport of huge quantities of waste; thus the potential threats to the human health and the environment that can arise during transportation can be avoided.
- It also helps in destruction of the complex pollutants, and many of the hazardous compounds can be transformed to harmless simple products; thus bioremediation can eliminate future liability of treatment and disposal of contaminated material.
- It does not use any hazardous or toxic chemicals. In general organic materials along with certain nutrients are used in the formulations.
- Less energy and manual supervision is required as compared to other technologies.

8 Limitations of Bioremediation

- Bioremediation is limited to only those compounds that are biodegradable. All heavy metal compounds are not susceptible to rapid and complete degradation.
- Biological processes are often highly specific. There are some concerns that the products of biodegradation may be more persistent or toxic than the parent compound.
- Suitable environmental growth conditions required for successful remediation include the presence of metabolically capable microbial populations and appropriate levels of nutrients and contaminants.
- It is difficult to extrapolate from bench and pilot-scale studies to full-scale field operations.
- Substantial gaps exist in the understanding of microbial ecology, physiology, and genetic expression and site specifications. Research is required to develop and engineer bioremediation technologies that are appropriate for sites with complex mixtures of contaminants which may be present as solids, liquids, or gases.
- Uncertainty remains regarding "clean" site as no performance evaluations criteria are there.

9 Scope and Future Directions

Through continued research, the remediation processes are likely to change in the future, with bioremediation technology becoming more sustainable and attractive than currently used physicochemical technologies. Recombinant DNA techniques have been studied intensively to improve the strength of microbes for the degradation of hazardous wastes under laboratory condition. The genetically engineered microorganisms have higher capacity of degradation and have been demonstrated successfully for the degradation of various pollutants under defined conditions. Bioremediation explores gene diversity and metabolic versatility of microorganisms (Boricha and Fulekar 2009). The genetic makeup of these microorganisms makes them valuable in bioaccumulation, biodegradation, biosorption, and biotransformation. The microbial genomics studies will deliver more robust technologies for the bioremediation of heavy metal-contaminated sites. There is a great optimism for future scientific advances in the discovery and development of novel bioremediation processes that can enhance the use of bioremediation. Developments in the use of microorganisms for the recycling of metal waste, with the formation of novel biominerals with unique properties, are also expected in the future.

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Reclamation of Sodic Soils in India: An Economic Impact Assessment

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1 Introduction

Land degradation due to sodicity is a major threat to agriculture in Indo-Gangetic plains. The salt-affected soils are widely distributed across the globe and occupy nearly 954.8 million hectares (Pessarakli and Szabolcs 1999). India has 6.73 Mha of salt-affected soils, of which 3.72 Mha is sodic soils predominantly present in Indo-Gangetic plains (Mandal et al. 2010). Sodic soils are characterized by the occurrence of excess Na^+ that adversely affects soil structure and crop growth (Qadir and Schubert 2002). The weathering of aluminosilicate minerals produces a continuous supply of sodium, potassium, calcium and magnesium salts in the catchment area. Due to arid and semiarid climate, the water evaporates in post-rainy months leave sodium carbonates (Na_2CO_3) and bicarbonates ($NaHCO_3$) on soil surface, which contribute to the formation of sodic soils in Indo-Gangetic plains (Chhabra 1996). Soil sodicity creates an inordinately high soil pH ranging from 8.5 to 11 in addition to the ion toxicity and high osmotic pressure (Lv et al. 2013). A high pH condition causes deficiencies of several important minerals which in turn inhibits the plant growth (Guan et al. 2009) and adversely affects the growth of early seedlings, grain yield (Chhabra 1996; Sharma et al. 2010) and grain quality (Rao et al. 2013). Low crop productivity in sodic soils is a serious concern due to increasing foodgrain demand. India's foodgrain demand projections (Radhakrishna and Ravi 1990; Kumar 1998; Kumar et al. 2009) suggest that the need to produce more food to

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an expanding human population will result in an increase in the use of poor-quality waters and soils for foodgrain production (Yadav 1981; Oster and Jayawardane 1998; Qadir et al. 2001).

More than 80 % farmers having sodic lands are marginal and small farmers. A significant advancement in the sodic land reclamation technology has been made in India to reclaim the degraded sodic soils and to enhance crop productivity for improving farm income of the farmers. The successful application of soil reclamation technologies at the farmer's fields has encouraged many states to launch ambitious programmes of land reclamation through land reclamation and development corporations by providing necessary inputs to augment the food and livelihood security of resource-poor farmers. However, literature on improvement in livelihood security of resource-poor farmers after reclamation of sodic lands has been very limited. Hence, this chapter is an attempt to assess the economic losses caused by sodic soils and impact on livelihood security of resource-poor small farmers due to sodic land reclamation in India.

2 Economic Losses from Sodic Soils

Salt-affected soils cause enormous production and monetary losses globally. However, there are no accurate global estimates of the damage caused by sodicity and salinity. It was observed in Mahewali irrigation command of Sri Lanka that the decline in crop productivity was one-third of salinity-free areas due to high salinity (Thiruchelvam and Pathmarajah 1999). Ghassemi et al. (1995) provided a few examples of aggregated estimates of monetary losses suffered by an economy from irrigation-induced soil salinity. In Pakistan, for example, the economy of Punjab province and the North-West Frontier Province suffer an estimated US$300 million annually from the decrease in farm production on soils slightly to moderately affected by salinity. Similarly, in the Republic of South Africa, the annual economic damage for the communities of Pretoria, Witwatersrand, Vereeniging and Sasolburg complex due to an increase of salt content in the Vaal Barrage was estimated to be US$29 million per year (Mareda and Pingali 2001). A recent Australian report (PMSEIC 1999) estimated that the loss of production due to salinity and rising water tables was about US$84 million per year, and the capital loss of land was about US$450 million. Ghassemi et al. (1995) reported annual income losses from salt-affected irrigated areas around US$12 billion. Qadir et al. (2014) estimated the annual economic losses on global level around US$27.3 billion from salt-affected irrigated areas.

Several studies have estimated the loss in farm production due to salt-affected soils in India by comparison of normal and salt-affected farms. In Gujarat, different levels of salinity decreased paddy yields by 10–80 %, and in Haryana farms having salinity had to leave 25 % of their lands as fallow as compared to only 4 % on farms without salinity (Joshi 1987; Chopra 1989). Soil degradation accounted

Table 1 Statewise production losses (t) due to sodicity in India

State	Cereals	Oilseeds	Pulses	Cash crops	Total production loss	Production loss (%)
Haryana	388,341	2112	2327	207,505	600,286	5.37
Punjab	143,233	205	431	95	143,964	1.29
Uttar Pradesh	3,997,858	64,391	129,014	3,363,377	7,554,640	67.56
Madhya Pradesh	15,478	9736	6297	516	32,026	0.29
Andhra Pradesh	15,752	10,944	75,344	185	102,225	0.91
Karnataka	9734	2686	2819	82	15,322	0.14
Tamil Nadu	53,356	13,697	4032	31,851	102,936	0.92
Gujarat	1,000,963	177,321	56,411	872,754	2,107,449	18.85
Maharashtra	0	19	1329	0	1348	0.01
Rajasthan	13,170	3220	4622	311	21,323	0.19
Bihar	314,792	2478	4713	179,228	501,212	4.48
Total	5,952,677	286,810	287,340	4,655,905	11,182,732	100

Source: Sharma et al. (2015)

25–46 % rice yield reduction and 56–78 % yield reduction in wheat in the Sharda Sahayak command area (Joshi and Jha 1991). A recent study estimated the losses caused by sodic soils in India from major crops (Table 1). Uttar Pradesh (67.56 %) and Gujarat (18.85 %) contributed higher production losses among the states. In terms of monetary value (Table 2), Uttar Pradesh contributed the highest monetary losses of ₹80.75 billion followed by Gujarat (₹51.49 billion), Haryana (₹6.55 billion), Bihar (₹5.06 billion), Andhra Pradesh (₹2.64 billion), Tamil Nadu (₹1.06 billion), Madhya Pradesh (₹0.88 billion), Rajasthan (₹0.39 billion) and Maharashtra (₹0.04 billion).

Every year, India loses 11.18 million tonnes of cereals, oilseeds, pulses and cash crops from 3.77 Mha of sodic area, which accounted the estimated loss of ₹150.17 billion (Table 3). Major contributors to the total production losses are cereals (53.23 %) and cash crops (41.63 %). Cereals accounted the monetary loss of ₹79.46 billion (53 %) in the total monetary losses. Among cereals, wheat accounted the highest loss of ₹49.96 billion (33.27 %) followed by rice (₹19.22 billion), pearl millet (₹5.35 billion) and maize (₹ 3.65 billion). This indicated that cereals contributed more than half of the total losses. Cash crops contributed 35 % (₹51.89 billion) to the total monetary losses, which is another major contributor after cereals (Table 2). The cotton (₹26.86 billion) and potato (₹18.76 billion) are the major contributors to the total monetary losses in cash crops. The contribution of oilseeds to monetary losses is ₹10.7 billion (7 %) in which groundnut (₹4.64 billion) and rapeseed and mustard (₹4.34 billion) are the major contributors. The share of pulses in the total monetary losses is ₹8.11 billion (5 %) and the major contributors are Bengal gram (₹3.9 billion) and pigeon pea (₹1.75 billion).

Table 2 Statewise monetary losses (₹) due to sodicity

State	Cereals	Oilseeds	Pulses	Cash crops	Total monetary loss	Monetary loss (%)
Haryana	5,284,156,637	70,518,849	75,900,935	1,124,459,979	6,555,036,400	4.36
Punjab	950,219,512	9,146,037	12,387,194	3,518,094	975,270,837	0.65
Uttar Pradesh	53,778,483,190	2,241,334,565	3,851,983,702	20,881,903,835	80,753,705,293	53.77
Madhya Pradesh	228,178,139	470,761,378	177,690,265	5,367,816	881,997,598	0.59
Andhra Pradesh	197,817,061	447,567,999	1,986,812,530	7,947,967	2,640,145,557	1.76
Karnataka	94,837,663	117,971,022	85,024,274	3,570,460	301,403,419	0.20
Tamil Nadu	670,734,119	196,747,547	109,958,654	89,969,054	1,067,409,374	0.71
Gujarat	13,894,547,757	6,974,853,315	1,521,104,646	29,107,080,430	51,497,586,147	34.29
Maharashtra	0	615,233	36,006,812	0	36,622,044	0.02
Rajasthan	177,776,036	96,372,305	122,246,976	3,212,223	399,607,540	0.27
Bihar	4,186,570,262	79,408,817	130,521,776	669,624,647	5,066,125,501	3.37
Total	79,463,320,376	10,705,297,066	8,109,637,764	51,896,654,505	150,174,909,711	100

Source: Sharma et al. (2015)

Table 3 Crop-wise production and monetary losses due to sodicity in India

Crop	Total sodic area (ha)	Production loss (t)	Monetary loss (₹ in million)	Monetary loss (%)	Production loss (%)
Rice	1,516,063	1,595,954	19,228	12.80	14.27
Wheat	1,934,043	3,602,908	49,963	33.27	32.22
Maize	224,242	284,076	3651	2.43	2.54
Pearl millet	412,348	393,397	5354	3.57	3.52
Sorghum	210,230	31,506	795	0.53	0.28
Barley	28,454	41,450	462	0.31	0.37
Ragi	16,015	3052	5	0.00	0.03
Other cereals	3586	334	5	0.003	0.00
Total cereals	*4,344,980*	*5,952,677*	*79,463*	*53*	*53.23*
Rapeseed and mustard	376,682	135,647	4346	2.89	1.21
Sesame	78,312	16,855	1528	1.02	0.15
Groundnut	221,182	128,952	4640	3.09	1.15
Soybean	88,600	4632	168	0.11	0.04
Sunflower	25,930	724	23	0.02	0.01
Total oilseeds	*790,706*	*286,810*	*10,705*	*7*	*2.56*
Bengal gram	379,770	147,746	3902	2.60	1.32
Pigeon pea	91,804	52,049	1750	1.17	0.47
Black gram	102,313	37,058	979	0.65	0.33
Green gram	68,167	24,307	627	0.42	0.22
Other pulses	36,073	26,181	851	0.57	0.23
Total pulses	*678,126*	*287,340*	*8110*	*5*	*2.57*
Cotton	421,367	615,342	26,867	17.89	5.50
Sugar cane	157,663	2,236,497	6262	4.17	20.00
Potato	380,246	1,804,066	18,768	12.50	16.13
Total cash crops	*959,276*	*4,655,905*	*51,897*	*35*	*41.63*
Total	6,773,088	11,182,732	150,175	100	100

Source: Sharma et al. (2015)

3 Investment and Economic Feasibility

In India, gypsum is the major source of soil amendment used to reclaim sodic soils. The use of other amendments like phosphogypsum, press mud, acid wash and molasses is limited (Chhabra et al. 1980). The investment depends on the quantity of gypsum required for reclamation, which depends on the amount of exchangeable sodium to be replaced, which in turn is governed by the amount of absorbed sodium in the soil, sodicity tolerance and rooting depth of the crop to be raised.

Gypsum is an important amendment used for sodic soil reclamation and a study has shown that 10–15 Mg of gypsum containing 70 % hydrated calcium sulphate ($CaSO_4 . 2H_2O$) is sufficient to reclaim 15 cm surface sodic soil of one hectare land

(Abrol and Bhumbla 1979). The actual quantity of gypsum required is calculated on the basis of laboratory tests carried out on the surface soil (0–15 cm). The capital investment of ₹76,284 is needed to reclaim one hectare sodic land (Table 4). The gypsum and its application cost is the major item (57.29 %) followed by tube well and its installation (19.66 %) and land development costs (16.26 %) in the total reclamation cost. The irrigation and flushing of salts are the other cost items (6.80 %) in the total investment cost. This indicates that a large amount of capital is required to reclaim salt-affected soils and it may not be possible for the resource-poor marginal and small farmers to bear this cost. Experiences in Haryana and Punjab revealed that there was negligible response for land reclamation without subsidy on gypsum (Joshi and Agnihotri 1982; Tripathi 2009). In order to encourage farmers for reclaiming the sodic land, the government provides subsidy on soil amendments ranging from 50 to 90 % through different antipoverty programmes.

Investment on land reclamation involves medium to long gestation periods. The economic feasibility analysis assumed 12 % opportunity cost of capital assuming the life periods of 20 years. The benefit-cost ratio of land reclamation was 2.47 (Table 5). The internal rate of return was 67 % and the payback period was 3 years. Several past studies also have highlighted the economic feasibilities of investment in rehabilitation and management of sodicity-affected lands (Joshi and Singh 1990; Tripathi 2011).

Land degradation resulting from soil salinity, sodicity or a combination of both, is a major impediment to productive utilization of land resources for crop production. Hence, reclamation of salt-affected agricultural land has assumed a paramount importance due to ever-growing food demand. Several technological options are available to ameliorate salt-affected soils. Over the past few decades, chemical amelioration for alkali soils in Indo-Gangetic regions of Punjab, Haryana and Uttar Pradesh has been well standardized. Similarly, development of drainage and water

Table 4 Capital required for sodic land reclamation

Particulars	Investment (₹ ha^{-1})	Share in total cost (%)
Land development	12,400	16.26
Tube well and its installation	15,000	19.66
Gypsum and its application	43,700	57.29
Irrigation and flushing	5184	6.80
Total investment	76,284	100

Note: Considered 2014 prices for estimation
Source: Authors estimation from survey data and discussions with experts

Table 5 Economic feasibility of land reclamation

Particulars	Indicator
Benefit-cost ratio	2.47
Internal rate of return (%)	67
Payback period (years)	3

Note: Considered 2014 prices for estimation
Source: Estimated by authors from survey data

Table 6 Status of sodic land reclamation in India

State	Sodic land reclaimed (ha)	Sodic land reclaimed (%)
Bihar	1807	0.09
Gujarat	38,300	1.96
Haryana	352,185	18.05
Karnataka	2900	0.15
Madhya Pradesh	100	0.01
Punjab	797,000	40.84
Rajasthan	22,400	1.15
Tamil Nadu	5100	0.26
Uttar Pradesh	731,550	37.49
Total	1,951,342	100.00

Note: *Data pertaining to the year 2014 and remaining data are as on 2006
Source: Tripathi (2011) and various government reports

management technology gave fillip to saline land reclamation activities in several states. With the support of the World Bank, European Union and other developmental agencies, India has reclaimed 1.95 Mha of sodic lands (Table 6). Across states, Punjab has reclaimed the largest sodicity-affected area (0.79 Mha), followed by Uttar Pradesh (0.73 Mha), Haryana (0.35 Mha), Gujarat (0.04 Mha) and Rajasthan (0.02 Mha).

4 Economic Impacts of Sodic Land Reclamation

4.1 Cropping Intensity

The land reclamation resulted in cropping pattern change, increase in gross cropped area and utilization of uncultivated farm lands. Cropping pattern has changed from cultivation of low to high value crops after reclamation of saline soils (Mandal et al. 2005; Ritzema et al. 2008). Datta (1995) reported that farmers in Haryana shifted from low value crop barley to high value crops like wheat and mustard after the installation of subsurface drainage. Several studies have reported that the land reclamation has increased cropping intensity (Datta et al. 2004a, b; Ritzema et al. 2008). A study conducted in Uttar Pradesh (Table 7) revealed that cropping intensity in pre-reclamation period was low (122.93 %) in alkalinity-affected area. The cropping intensity in *rabi* season was 47.95 % in pre-reclamation period as land under 'moderate' and 'severe' categories was left fallow due to high levels of sodicity. This indicated that the cropping intensity decreased with increase in soil sodicity levels. All uncultivated degraded lands in pre-reclamation period have been put under cultivation after land reclamation. Hence, the cropping intensity was 199.54 % and increased by 62.32 %. The increased cropping intensity contributed to higher total farm production and income.

Table 7 Impact of sodic land reclamation on cropping intensity (%)

Soil sodicity class	Pre-reclamation period	Post-reclamation period
Normal	198.50	198.47
Slight	193.25	199.73
Moderate	99.96	199.93
Severe	0.00	200.00
Average in *kharif*	73.98	99.77
Average in *rabi*	48.95	99.77
Annual average	122.93	199.54

Source: Thimmappa et al. (2015a)

Table 8 Impact of sodic land reclamation on crop yields

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Yield (Mg ha^{-1})	4.87	2.95	1.22	0
		Yield loss (%)	–	39.43	74.95	100
	Post-reclamation period	Yield (Mg ha^{-1})	4.97	4.71	4.40	3.90
		Yield loss (%)	–	5.24	11.48	21.45
	Mean difference between post- and pre-reclamation periods		–	1.76*	3.18*	–
Wheat	Pre-reclamation period	Yield (Mg ha^{-1})	3.65	2.82	0	0
		Yield loss (%)	–	22.74	100	100
	Post-reclamation period	Yield (Mg ha^{-1})	3.74	3.49	3.17	2.75
		Yield loss (%)	–	6.82	15.24	26.60
	Mean difference between post- and pre-reclamation periods		–	0.67*	–	–

*Significant at $p \leq 0.05$ level
Note: In pre-reclamation period, the severely sodicity-affected lands were left fallow in both seasons and no crop production in 'moderate' classes during *rabi* season
Source: Thimmappa et al. (2015a)

4.2 Productivity and Unit Cost of Production

Yield loss is detrimental at a local scale because salt-affected soils are not uniformly distributed. It was observed in sodic areas of Uttar Pradesh that the salt concentration in soil has steeply reduced the crop yield (Table 8). The rice yield decreased from 4.87 Mg ha^{-1} in 'normal' soils to 2.95 Mg ha^{-1} in 'slight' soil sodicity class, indicating 39.43 % decline. Several studies have shown that crop yield decreases with increase in the level of sodicity (Abrol and Bhumbla 1979; Chhabra 2002; Dwivedi and Qadar 2011). The yield reduction was drastic (74.95 %) in 'moderate' soil sodicity class. A large number of studies indicated that the sodicity inhibits shoot and root growth of rice seedlings and had less biomass when grown under sodic conditions (Chhabra 1996; Van Aste et al. 2003: Wang et al. 2011). Wheat yield decreased from 3.65 Mg ha^{-1} in 'normal' soil to 2.82 Mg ha^{-1} in 'slight' land class, depicting 22.74 % yield loss. The yield loss of wheat was greater at the higher sodicity levels (Sharma et al. 2010). Yield of wheat is highly dependent on the number of spikes produced by each plant. Sodic conditions negatively affect the number of spikes produced per plant (Maas and Grieve 1990) and the fertility of the spikelets (Fatemeh et al. 2013). Sodic soils usually have poor availability of most micronutrients, which is generally attributed to high soil pH (Naidu and Rengasamy 1993).

In addition, poor physical properties of sodic soils, which directly limit crop growth through poor seedling emergence and root growth, also exhibit indirect effects on plant nutrition by restricting water and nutrient uptake and gaseous exchange (Curtin and Naidu 1998) which ultimately result in reduced crop yield and quality (Grattan and Grieve 1999). There was no wheat production in 'moderate' and 'severe' soil sodicity classes. A high pH condition damages plants directly and causes deficiencies of nutritional minerals such as iron and phosphorus (Guan et al. 2009). The 'severe' category of soil sodicity class remained barren in both the seasons due to high sodicity as ESP ranged from 65 to 90 and pH varied from 9.5 to 11. Heavy salt stress generally leads to reduced growth and even plant death (Qadar 1998; Parida and Das 2005).

Rice-wheat rotation is most common in Indo-Gangetic plains. It was noticed that land reclamation had a profound impact on productivity of rice and wheat. Before reclamation, the productivity of rice was 2.95 Mg ha^{-1} in 'slight' and 1.22 Mg ha^{-1} in 'moderate' land categories. The productivity of rice increased to 4.71 Mg ha^{-1} in 'slight' soil sodicity category after reclamation, depicting a gain of 60 %. In 'moderate' soil sodicity category, rice productivity increased to 4.40 Mg ha^{-1}, indicating a remarkable increase of 261 %. Hence, a significant yield gain was observed in rice after land reclamation. In the 'severe' soil sodicity category, rice production was 3.90 Mg ha^{-1} which was barren in pre-reclamation period. Similarly, wheat production was 2.82 Mg ha^{-1} in 'slight' land category in pre-reclamation period and increased to 3.49 Mg ha^{-1} in post-reclamation period. The wheat yield was 3.17 Mg ha^{-1} in 'moderate' and 2.75 Mg ha^{-1} in 'severe' land sodicity categories in post-reclamation period which were uncultivated in pre-reclamation period. It suggested that a significant yield gain was observed after land reclamation. The yield gain was highest in 'moderate' class (3.17 Mg ha^{-1}) followed by 'severe' (2.75 Mg ha^{-1}) and 'slight' (0.67 Mg ha^{-1}) sodicity classes.

The rice yield losses were ranged from 39.43 to 100 % in pre-reclamation period compared with normal land. The yield losses were reduced and ranged from 5.24 to 21.45 % in post-reclamation period. Similarly, wheat yield losses were varied from 22.74 to 100 % in pre-reclamation period. The losses were substantially reduced and ranged from 6.82 to 26.60 % after reclamation. Chinnappa and Nagaraj (2007) reported that subsurface drainage technology had a profound impact on crop productivity and increased the average crop productivity by 166 %. A large number of experimental results and on-farm studies showed that proper adoption of reclamation techniques has produced yields on par with the yield of normal soils (Joshi 1983; Singh and Bajaj 1988; Datta et al. 2004a, b). The higher crop productivity in post-reclamation period was due to better soil condition for crop production. The installation of subsurface drainage has substantially decreased soil salinity. Several studies have proved that the application of gypsum decreases sodium toxicity and improves soil structures which contribute to crop productivity improvement to a greater extent (Chhabra 1996; Rasouli et al. 2013). Hence, soil reclamation played a great role in augmenting crop yields in degraded sodic soils.

The unit cost of production has been affected by varying levels of salt accumulation in the soil. For example, sodicity has remarkably increased per Mg cost of rice by 260.15 % in 'moderate' soil class compared to 'normal' soil class in sodic areas of Uttar Pradesh (Table 9). This indicates that production costs per Mg of produce increase from lower to higher sodicity classes, due to lower crop productivity at the higher level of soil sodicity. The cost per Mg of rice was reduced from ₹13,663 to 9431 in 'slight' soil sodicity category in the post-reclamation period, indicating 30.97 % reduction. The cost Mg^{-1} of rice was steeply reduced by 67.36 % in 'moderate' soil sodicity category in post-reclamation period. The per Mg cost incurred for wheat production was 18.55 % higher in 'slight' sodicity class in pre-reclamation period and declined to 5.23 % in post-reclamation period compared to normal land. This indicates that costs Mg^{-1} of produce declined after reclamation due to higher crop productivity across different soil sodicity categories. Even after reclamation, still soil sodicity exists in different soil sodicity category lands in varying levels ranged from 8.48 to 9.09 pH. Gradually, the extent of sodicity would be reduced and soils become normal. Several studies conducted at the Central Soil Salinity Research Institute revealed that after amendments application and leaching of salts and continuous cropping of rice-wheat-*Sesbania* crop rotation at least for 4–6 years are required for successful reclamation of the sodic soils (Chhabra and Abrol 1977; Singh et al. 1998; Tyagi 1998; Swarup 2004).

Table 9 Impact of sodic land reclamation on unit cost of production

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Costs (₹Mg^{-1})	8560	13,598	30,828	–
		Change (%)	–	59.62	260.15	–
	Post-reclamation period	Costs (₹Mg^{-1})	8951	9431	10,062	11,017
		Change (%)		5.36	12.41	23.08
	Mean difference between post- and pre-reclamation periods		–	4167*	20,766*	–
Wheat	Pre-reclamation period	Costs (₹Mg^{-1})	9475	11,232	–	–
		Change (%)		18.55	–	–
	Post-reclamation period	Costs (₹Mg^{-1})	9200	9681	10,457	11,437
		Change (%)		5.23	13.67	24.30
	Mean difference between post- and pre-reclamation periods		–	1551*	–	–

*Significant at $p \leq 0.05$ level

Note: No crop production in 'severe' sodicity class land in *kharif* season. In pre-reclamation period, no crop production in 'moderate' and 'severe' sodicity class land in *rabi* season

Source: Thimmappa et al. (2015b)

Table 10 Impact of sodic land reclamation on costs and returns (₹ ha^{-1})

Sodicity class	Gross return		Total cost		Net returns		Total net returns
	Kharif	*Rabi*	*Kharif*	*Rabi*	*Kharif*	*Rabi*	
Pre-reclamation period							
Normal	77,290	58,320	41,715	34,614	35,575	23,706	59,281
Slight	47,120	45,032	40,351	31,707	6769	13,324	20,094
Moderate	19,470	–	37,597	–	−18,127	–	−18,127
Post-reclamation period							
Normal	79,278	59,740	44,442	34,396	34,836	25,344	60,180
Slight	75,143	55,548	44,366	33,732	30,777	21,815	52,592
Moderate	68,958	50,670	44,214	33,088	24,743	17,582	42,325
Severe	62,275	43,558	42,964	31,342	19,311	12,216	31,527

Note: 'Moderate' sodicity category lands were kept fallow only in *rabi* season. 'Severe' sodicity category lands were kept fallow in both the seasons during pre-reclamation period
Source: Thimmappa et al. (2015a)

4.3 Farm Income and Employment

The study conducted in sodic soils indicated that the crops gross income decreased with increase in soil quality deterioration (Table 10). Net income decreased more sharply than gross income with increase in sodicity level, because the total cost of production remained almost uniform throughout the soil sodicity classes. The net income per ha from 'slight' land class was lower (₹6769) compared to net income (₹35,575) from 'normal' land during *kharif* season, depicting a loss of 80.97 %. The farmers incurred per ha income loss of ₹18,127 in 'moderate' soil sodicity class. In *rabi* season, decline in the net income was 43.79 % in 'slight' soil sodicity class and the 'moderate' sodicity-affected lands were kept fallow. The rate of income loss increased with higher levels of sodicity. Hence, it was clear that the soil sodicity adversely affected net income across soil sodicity classes and income losses were greater in higher sodicity levels.

The net return per ha was ₹20,094 in 'slight' soil sodicity category in pre-reclamation period and increased to ₹52,592 in post-reclamation period, indicating a gain of 161.73 %. Farmers incurred loss in 'moderate' soil sodicity category during pre-reclamation period and the per ha income has steeply increased to ₹42,325 after reclamation. The increased productivity contributed to higher net income across the soil sodicity categories. In the 'severe' soil sodicity category, net income was ₹31,527 which was left fallow in pre-reclamation period. It indicated that income could be generated by reclamation of severely degraded barren land. Several studies also have reported that land reclamation benefited farmers in terms of reduction in income losses and enhanced farm income (Joshi 1983; Chinnappa and Nagaraj 2007).

Farmers in the sodicity-affected area generally migrate to urban areas in pursuit of employment. A study in sodic areas in Uttar Pradesh observed that the land reclamation is changing these situations as increase in cultivated area and productivity

Table 11 Impact of land reclamation on farm labour employment

Particulars			Normal	Slight	Moderate	Severe
Rice	Pre-reclamation period	Employment (man-days ha^{-1})	144	135	117	0
	Post-reclamation period	Employment (man-days ha^{-1})	142	141	140	132
	Additional employment generation (man-days ha^{-1})		–	6	23	132
Wheat	Pre-reclamation period	Employment (man-days ha^{-1})	81	71	0	0
	Post-reclamation period	Employment (man-days ha^{-1})	81	80	77	70
	Additional employment generation (man-days ha^{-1})		–	9	77	70

Source: Thimmappa et al. (2015b)

enhancement generated additional employment (Table 11). The reclamation generated additional farm employment to farming families. The reclamation of barren land generated highest employment annually in rice (132 man-days ha^{-1}) and wheat (70 man-days ha^{-1}). The reclamation of 'severe' category land generated employment of 202 man-days ha^{-1} annually. The slightly affected lands have marginally contributed to employment generation. The total annual employment generation varied from 15 to 202 man-days ha^{-1}. Land reclamation generated additional employment due to additional barren land brought under cultivation and increased cropping intensity (Joshi 1983; Joshi and Singh 1990; Tripathi 2011; Thimmappa et al. 2013).

4.4 Foodgrain Availability

Land degradation will remain an important issue due to its adverse impact on marginal and small farm household's food security. The Indian government has been implementing a wide range of programmes to achieve food and nutritional security at the household and individual levels. Land reclamation programme is one of the programmes implemented by central and state governments to improve the income and livelihood security of marginal and small farmers. The direct effect of reclamation in Santaraha village in Uttar Pradesh was noticed on food security status of the marginal and small farm households (Table 12). The total rice and wheat requirement per family was estimated from 66th round NSSO (NSSO 2000; NSSO 2010) survey for pre- and post-reclamation periods. The foodgrain self-sufficiency was calculated as the difference between the total annual production of rice or wheat and total annual family consumption. The rice and wheat produced by marginal and small farmers were insufficient for family consumption in pre-reclamation period. The situation has changed after reclamation. All category farmers produced excess

Table 12 Foodgrain availability status of different categories of farmers

Particulars		Marginal farmers	Small farmers
Pre-reclamation period			
Milled rice	(a) Production (Mg family^{-1} year^{-1})	0.134	0.348
	(b) Consumption (Mg family^{-1} year^{-1})	0.356	0.356
	(c) Deficit/excess (Mg family^{-1} year^{-1})	−0.222	−0.008
Wheat	(a) Production (Mg family^{-1} year^{-1})	0.105	0.000
	(b) Consumption (Mg family^{-1} year^{-1})	0.633	0.633
	(c) Deficit/excess (Mg family^{-1} year^{-1})	−0.528	−0.633
Post-reclamation period			
Milled rice	(a) Production (Mg family^{-1} year^{-1})	0.747	2.183
	(b) Consumption (Mg family^{-1} year^{-1})	0.356	0.356
	(c) Deficit/excess (Mg family^{-1} year^{-1})	0.391	1.827
Wheat	(a) Production (Mg family^{-1} year^{-1})	1.012	2.959
	(b) Consumption (Mg family^{-1} year^{-1})	0.633	0.633
	(c) Deficit/excess (Mg family^{-1} year^{-1})	0.379	2.325

Note: Figures in parentheses indicate percentage to the total. The negative sign indicates the foodgrain deficit
Source: Thimmappa et al. (2015b)

rice and wheat in their farm due to significant increase in the farm productivity. The farmers were extremely happy with the abundant foodgrain production and acknowledged that the attainment of foodgrain self-sufficiency brings a great satisfaction to them.

The foodgrain production of individual farm households varied among the same category due to variation in the farm size which ranged from 0.05 to 0.9 ha across for marginal farmers and 1.00–1.17 ha per family across small farmers. The marginal and small categories of farmers were subclassified into deficit foodgrain-producing households and foodgrain self-sufficient households. This classification is based on the difference between per household per annum total rice or wheat requirement for consumption and production. The households with annual consumption requirement more than annual production were classified as food-deficit households and were assumed to have low food security status. The households with annual production more than annual consumption requirement were classified as food self-sufficient households.

The distribution of households by foodgrain self-sufficiency status (Table 13) revealed that 81.25 % of marginal farmers and 61.54 % of small farmers were not producing sufficient quantities of rice for family consumption in pre-reclamation period. Similarly, 90.63 % of marginal farmers were not producing sufficient quantities of wheat required for family consumption. The small farmers were having only ‘moderate’ and ‘severe’ categories of land which were kept fallow in rabi season. Hence, small farmers met the entire quantity of wheat for family consumption from outside source. After land reclamation, 82.81 and 59.38 % of marginal farmers became self-sufficient in rice and wheat production, respectively. Not all marginal

Table 13 Distribution of households by foodgrain self-sufficiency status (figures in %)

Categories of farmers	Foodgrains	Pre-reclamation period		Post-reclamation period	
		Deficit	Sufficient	Deficit	Sufficient
Marginal	Milled rice	81.25	18.75	17.19	82.81
	Wheat	90.63	9.38	40.63	59.38
Small	Milled rice	61.54	38.46	0.00	100.00
	Wheat	100.00	0.00	0.00	100.00

Source: Thimmappa et al. (2015b)

farmers could achieve self-sufficiency in foodgrain production due to smaller farm size. Small farmers achieved self-sufficiency in rice and wheat production and could sell excess foodgrains in the market. Due to increased production, majority of the farm households achieved self-sufficiency in the availability of major foodgrains for family consumption in post-reclamation period.

4.5 Agribusiness and Household Expenditure

Society has significantly benefited by the reclamation of sodic lands. A study observed that the farm output and input related agribusiness industries business annual transactions have increased by ₹83,537 million in Uttar Pradesh due to sodic land reclamation (Table 14). Land reclamation in Uttar Pradesh contributed the highest business transaction in foodgrain agribusiness sector annually (₹59,114 million) which accounted 71 % in the total contribution. It generated additional employment of 94 million man-days (₹14,083 million) per annum which is the next major contributor accounted 17 %. The land reclamation has generated large business opportunities to other agribusiness sectors like seed (₹4194 million), fertilizer (₹5230 million) and pesticide (₹914 million) industry sectors.

The other social benefits of land reclamation included the improvement in income distribution among farm households. Several studies have reported that the land reclamation helped in reducing income inequality among the farm households (Joshi and Agnihotri 1982; Thimmappa et al. 2013; Chinnappa and Nagaraj 2006). Tripathi (2011) reported that land reclamation resulted in poverty reduction and varied from 39 to 43 % among different categories of farmers.

The household expenditure pattern has been influenced by the enhanced farm income due to land reclamation. The majority of farmers (92 %) opined that purchasing of foodgrain, especially of rice and wheat, from the market had declined (Table 15). A considerable number of farmers (65 %) opined that the purchasing of nonfood commodities like clothes and other household items has increased after reclamation. A few farmers opined that the expenditure on fruits and vegetables purchase has increased. A rise in expenditure on house construction and children education was also reported after reclamation. Hence, land reclamation made a substantial improvement in the socio-economic well-being of the farm families in the salt-affected regions.

Table 14 Impact of sodic land reclamation on agribusiness sector

Business sectors	Value (₹ million)
Employment	14,083
Seed	4194
Fertilizer	5230
Foodgrains	59,114
Pesticides	914
Total	83,537
Contribution of one ha reclaimed land per annum	0.12

Source: Thimmappa et al. (2015b)

Table 15 Impact of sodic land reclamation on household expenditure (%)

Particulars	Increased	Decreased	Constant	No difference
Foodgrain purchase	0	92	8	0
Fruit purchase	17	0	83	0
Vegetable purchase	18	13	68	0
Purchasing of clothes	65	0	25	10
Investment on house construction	78	0	22	0
Education expenditure	73	0	17	10

Source: Thimmappa et al. (2013)

5 Conclusion

Land degradation caused by sodicity is a serious threat to the future of agriculture in India. India loses annually 11 million Mg of farm production valued at ₹150 billion due to sodic soils. In view of this, governments in the salt-affected areas have launched ambitious programmes of land reclamation through land reclamation and development corporations by providing necessary inputs to augment the livelihood security of resource-poor farmers. Over the past few decades, with the support of the World Bank, European Union and other developmental agencies, India has reclaimed 1.95 Mha of sodic lands, which contributed enormous socio-economic benefits and livelihood security to millions of resource-poor farmers living in the salt-affected regions. The impact of land reclamation showed a significant scope for poverty reduction in the rural sector, and sodic land reclamation programmes need to be continued to uplift the marginal and small farmers out of poverty.

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Bioremediation of Salt-Affected Soils: Challenges and Opportunities

Sanjay Arora, Atul K. Singh, and Divya Sahni

1 Introduction

India is situated in arid and semiarid region where high evapotranspiration results in accumulation and deposition of salt contents on the soil surface. Precipitation, waterlogging, poor drainage, clearing of trees, seawater ingress in coasts, canal seepage, and over-irrigation are some of the major factors contributing to soil salinity, while soil sodicity is mainly geogenic. The harmful effects of presence of salts in soil result in increased level of ethylene in roots, ionic imbalance, and hyperosmotic condition in plants (Niu et al. 1995; Zhu et al. 1997; Mayak et al. 2004). Physical removal of salts from the surface of soil or chemical treatment of soil is not only expensive but can't be applied to vast areas for soil reclamation purposes. The solution lies with using phytoremediation or vegetative bioremediation (i.e., using the halotolerant plants) or bioremediation (using the salt-tolerant bacteria) for reclamation of salt-affected soils on large scale (Rajput et al. 2013).

During the last few years, the main remedial action for amelioration of salt-affected soils has been replantation through salt-tolerant plant species. There is an urgent need for raising crops capable of growing under salt-stress environments to enable agriculture on marginal lands. Studies have established that a high salt concentration in the vicinity of a plant manifests itself by disrupting the ability of the roots for efficient water uptake, thereby leading to perturbation of crucial metabolic reactions inside the cell. It is vital to use salt-affected wastelands to produce forage and fuel as a result of pressure on existing land resources where economic halophytes can be a better option. These plant species can not only grow under salt stress but can be a source of income apart from ecological restoration of these degraded lands. There are certain multipurpose agroforestry plant species that are salt tolerant

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and can be grown on soils laden with salts. Salt-tolerant crop varieties have been developed for cultivation on saline and sodic soils, which also have potential to restore these degraded lands.

Halophilic microorganisms are organisms that grow optimally in the presence of high NaCl concentrations. The high potential for bioremediation applications using halophilic bacteria and fungi has been reported by several workers. The applications of halophilic bacteria include recovery of salt-affected soil by directly supporting the growth of vegetation, thus indirectly increasing crop yields in salt stress (Arora et al. 2014b). The biotic approach “plant-microbe interaction” to overcome salinity/sodicity problems has recently received a considerable attention from many workers throughout the world. Bacteria are the most commonly used microbes in this technique. Vesicular-arbuscular mycorrhiza, or VAM fungi, is also found to be very effective in alleviating salt stress. With the possibility of application of halophilic bacteria in saline soil recovery and the importance of microbial diversity in soil, the study of halophilic bacterial diversity in saline soil is important in order to realistically access their future application in the rehabilitation of saline-degraded lands. In addition, the halophilic bacterial isolates obtained can be used for the study of other potential applications. This all will help in bioremediation of saline soil and improve the crop yields and in turn help in uplifting the socioeconomic status of the farming community. However, there are great opportunities and challenges for the future of bioremediation techniques for effective reclamation of salt-affected soils.

2 Vegetative Bioremediation or Phytoremediation

Amelioration of saline and sodic soils has been predominantly achieved through the application of chemical amendments. However, amendment costs have increased prohibitively over the past two decades due to competing demands from industry and reductions in government subsidies for their agricultural use in several developing countries (Qadir et al. 2007). Saline soil improvement needs excessive amount of good quality water to wash salts as ameliorative measure. In many countries in arid and semiarid regions where rainfall is scanty and the availability of good quality waters that too in huge quantities is a problem, this method of reclamation is not recommended. However, other biological methods can be used such as planting the soil with salt-tolerant plants where salts are taken up by these plants and removed from the soil. For farmers, bioremediation is very useful as it requires low initial investments and improves the soil quality and the produced crops can be used as food and fodders. Since climate and cost are two vital factors in reclamation of salt-affected land, hence, cultivation of salt-tolerant species could be an effective way to improve this situation (Akhter et al. 2003).

Recently, a new environmentally safe and clean technique known as vegetative bioremediation or phytoremediation has been introduced to address the problem of soil salinity or sodicity. This includes the introduction of salt (ion)-removing species to control salinity/sodicity and to maintain the sustainability of agricultural fields (Rabhi et al. 2008; Ashraf et al. 2010; Ravindran et al. 2007). Phytoremediation is defined as the use of plants to remove pollutants from the environment and to render them harmless (Salt et al. 1998). These plants not only remediate the salt-contaminated soils but also provide food, fodder, fuelwood, and industrial raw material and increase the income of the farmers owning salt-affected lands. To maximize crop productivity, the salt-affected lands should be brought under utilization where there are options for removing salinity or using the salt-tolerant crops. The use of salt-tolerant crops and halophytes have the capacity to accumulate and exclude the salts and thus can be an effective way to remediate salt laden soils (Hasanuzzaman et al. 2014).

Phytoremediation has, however, been found to be economically feasible when there is a market demand for the phytoremediation crop or when the crop can be used locally at the farm level (Sandhu and Qureshi 1986; Chaudhry and Abaidullah 1988). Qureshi et al. (1993) found that agroforestry systems comprising several tree species were economically viable because of a high demand for firewood in local markets and because the trees were effective in ameliorating calcareous saline-sodic soils. Clearly, from an economic perspective, the success of a phytoremediation technique depends, to a large extent, on local needs and markets (Qadir et al. 2005). In the short term, phytoremediation strategies can only be economically beneficial if there is market demand for the selected crops, grasses, or trees, or if they are useful locally at the farm level. However, in any economic analyses of sodic soil amelioration, it is also important to consider the long-term benefits of improvements made to the soil and the environment.

3 Halophytes for Bioremediation: Future Prospects

Growing halophyte plants under saline conditions had been reported. Boyko (1966) was the first to suggest that halophytic plants could be used to desalinate soil and water. Halophytes are characterized as plants that can survive and reproduce in environments where the salt concentration exceeds 200 mM of NaCl (~20 dSm^{-1}), according to Flowers and Colmer (2008). These species constitute approximately 1 % of the world's flora. Halophytes are plants capable of completing their life cycle under highly saline (NaCl) conditions (Stuart et al. 2012). Halophytes are also called euhalophytes because they have increased productivity with increasing salt levels and actually grow better under salinity condition than under freshwater conditions (Yensen 2008). These halophytes possess special morphological and anatomical features as well as physiological processes which are well suited to cope with saline environments. The halophytes can effectively improve the saline soil as they are well adjusted in salt environment because of their diversified adaptation mechanisms including ion compartmentalization, osmotic adjustment, succulence, ion transport and uptake, antioxidant systems, maintenance of redox status, and salt inclusion or excretion (Lokhande and Suprasanna 2012). It has been reported that plants of economic value can be used for reclamation of saline and sodic soils. Using *Portulaca* *oleracea L.* as a salt removal crop was reported by Kilic et al. (2008) where they showed that considerable amounts of salt from soil were removed after planting this plant species. Bioremediation of saline soils in Jordan was studied by Al-Abed et al. (2004) at a laboratory scale using aerobic bacteria where they found that bacteria were very efficient in reducing the EC values in the first week of application. Several halophytic plant species have been used in the reclamation and vegetation restoration of salt-affected soils (Al-Nasir 2009; Tanner and Parham 2010).

It is necessary and important to know the salt tolerances of different species seeds that grow in saline and alkaline conditions. Seed germination of species in saline substrates is a legitimate criterion in selecting halophytes for saline environments (Sosa et al. 2005) and developing vegetation restoration (Zheng et al. 2005). However, halophyte species vary in their tolerance to salinity during seed germination. For some species, low concentrations of NaCl do not inhibit germination; they may even enhance it (Croser et al. 2001; Huang et al. 2003). However, previous studies have primarily focused on seed germination responses for only one or two specific species. The information available on the germination of halophytic seeds is far from complete (Khan and Gul 2006); although there are roughly 2400 known halophytic species, the availability of data regarding germination is patchy. A better understanding of interspecific variation to salinity stress would be constructive from both basic and applied perspectives and would be especially important for identifying plant species for specific restoration and remediation projects (Easton and Kleindorfer 2009).

There are diversified species of halophytes suited to grow in different saline regions throughout the world, namely, coastal saline soil, soils of mangrove forests, wetland, marshy land, lands of arid and semiarid regions, and agricultural fields. These plants can be grown in land and water containing high salt concentration, can be substitute for conventional crops, and can be a good source of food, fuel, fodder, fiber, essential oils, and medicine. At the same time, halophytes can be exploited as significant and major plant species bearing potential capability of desalination and restoration of saline soils and phytoremediation as well. By developing these precious strategies, unused and marginal land can be brought under cultivation, and existing agricultural land will be more productive which will open a new door to sustain crop productivity.

Several halophytic plant species have been tried in the past for their possible use in reclamation of salt-affected soils (Ravindran et al. 2007; de Villiers et al. 1995; Gul et al. 2000; Jithesh et al. 2006). After conducting number of experiments, several researchers found phytoremediation to be an effective amelioration strategy for calcareous saline-sodic and sodic soils with comparable performance against the use of chemical amendments (Singh et al. 1989; Ahmad et al. 1990; Qadir et al. 1996). Besides their positive impact on salt-affected soils, the potential use of some halophytes as forage and as oilseed crops has also been described (Glenn et al. 1999). Phytoremediation potential of six halophytic and other salt-tolerant economically useful plant species, i.e., *Suaeda nudiflora*, *Avicennia marina*, *Suaeda oleiodes*, *Hibiscus* sp., *Indigofera oblongifolia*, and *Murraya koenigii*, was assessed under pot experiment, and it was observed that increased salinity resulted in increased accumulation of sodium in leaves of these plants indicative of their salt removal efficiency. It was observed that maximum amount of salt was removed by *Suaeda nudiflora* (Arora et al. 2013). According to Qadir et al. (2007), phytoremediation has been advantageous in several aspects: (1) no financial outlay to purchase chemical amendments, (2) accrued financial or other benefits from crops grown during amelioration, (3) promotion of soil aggregate stability and creation of macropores that improve soil hydraulic properties and root proliferation, (4) greater plant nutrient availability in soil after phytoremediation, (5) more uniform and greater zone of amelioration in terms of soil depth, and (6) environmental considerations in terms of carbon sequestration in the post-amelioration soil.

Vegetative bioremediation or bioreclamation of salt-affected soils is an economic solution mainly for developing countries since chemical additions are becoming increasingly expensive. Several authors (Rabhi et al. 2009; Ravindran et al. 2007) have proved that the potential of halophytic plants to accumulate enormous salt quantities depends often on the capacity of their aboveground biomass (hyperaccumulating plants). This ability could be of great importance, particularly in arid and semiarid regions, where insufficient precipitations and inappropriate systems are unable to reduce the salt burden in the rhizosphere of plants (Shiyab et al. 2003) and suitable physicochemical methods are too expensive. Environmentally safe and clean technique to address the salinity problem includes the introduction of salt (ion)-removing species to control salinity and to maintain the sustainability of agricultural fields. Large-scale decontamination of soils and underground water using phytoremediation techniques requires plants with high salt uptake rates, large biomass, and tolerance to a wide array of environmental conditions and constraints. Furthermore, salt marshes, especially salt-accumulating halophytes, are dominant crop in the coastal region, and introduction of these salt-removing halophytic species could potentially create both environmental and economic solutions to remediate saline soils.

4 Halophytes for Remediating Toxic Metals

The study of halophytes can be useful from three perspectives (Glenn et al. 1999): First, the mechanisms by which halophytes survive and maintain productivity on saline soil/water can be useful to develop tolerant varieties in conventional crops (Rausch et al. 1996; Serrano 1996; Glenn et al. 1997; Zhu et al. 1997). Second, halophytes grown in an agronomic setting can be used to evaluate the overall feasibility of high-salinity agriculture (Glenn et al. 1997, 1999). Third, halophytes may become a direct source of new crops (Ashraf et al. 2010; Glenn et al. 1997; O'Leary 1994). Apart from accumulation of salt from the saline habitat, many of the halophytes are capable of remediating toxic metals and can grow and give yield. Halophytes are often adapted well in metal-affected habitat compared to glycophytic plants which makes them a good candidate as an eco-friendly and sustainable solution of contaminated coastal environment cleanup (Anjum et al. 2014).

5 Germplasm Collection and Development

Collection and preservation of seed and germplasm are perhaps the most immediate priorities before halophytes can be bred for commercial and environmental purposes. The availability of seed and germplasm for research, breeding, and experimentation must be secured by both public and private institutions as an extended gene pool will prove invaluable for future domestication. Due to the myriad of factors influencing plant response to salinity, attention should be given to the identification and collection of genotype or population variations among the most promising species. Germplasm collection and preservation must be given precedence until the economic value of halophytes is fully recognized, markets are established, and commercial seed companies begin to take over this function.

6 Breeding Programs

Past and present utilization often determines the relevant properties to be screened, i.e., salt tolerance, nutritional value, palatability, and digestibility. Other considerations include their adaptability to diverse habitats and current agricultural infrastructure/technology including production, processing, and distribution. The aim of breeding cultivars with commercial value and/or other economic incentives linked to conservation involves the continuous improvement of crop characteristics and shifting halophyte programs from the greenhouse into the field.

7 Commercial Viability

The prospect for adopting halophytes in commercial agricultural production depends on a number of economic factors including the cost of saline resources (soil and water) and other inputs, plant yield assessments, harvesting, processing, and marketing requirements, consumer and end-user acceptance as well as the appropriate valuation of associated environmental costs and benefits. For halophytic crops, the cost of more abundant saline resources (i.e., land and water) is often significantly lower than those needed for freshwater cultivation; the design, planting, and management of salt-tolerant crops on previously irrigated farms may further reduce costs by taking advantage of existing on- and off-farm infrastructure (i.e., irrigation, drainage, and mechanization). Actual yields per hectare and the cost of harvesting, processing, and marketing halophytic produce are also important considerations in evaluating their commercial feasibility. However, until the environmental costs (of chemical monocultures) and benefits (of halophyte cultivation) are properly monetized, traditional cost/benefit analysis will be unable to accurately reflect the economic viability of halophytes.

8 Screening, Selection, and Breeding

Conventional breeding techniques (i.e., screening, recurrent selection, and interspecific hybridization) that exploit existing genetic variability have historically demonstrated the greatest potential for designing new cultivars and increasing salt tolerance among existing crops. These ancient methods for improving crop characteristics through the deliberate reproduction of superior plants still hold tremendous promise for domesticating wild species and developing economically useful crops with higher salinity thresholds. Recurrent selection (the recombination of individual plants) can then be utilized for the creation of salt-tolerant populations that did not previously exist. Although it may take many generations of crosses before these desirable traits are reinforced and the undesirable ones eliminated, accelerated breeding programs can lead to the formation of new varieties within a few years (in some cases). More advanced breeding programs involve controlled interspecific crosses (between species of the same genus) among selected parentage that demonstrate salt tolerance as well as desirable crop traits. Researcher at the University of California, Davis produced a number of commercial tomato hybrids in the 1970s by crossing domesticated varieties (*Lycopersicon esculentum*) with inedible wild species (*L. peruvianum, L. pennellii*, and *L. cheesmanii*) from South America. By just pushing the envelope of salt tolerance, improved crop varieties can extend the arable life of salt-affected soils currently under cultivation as well as restore marginal lands to agricultural production. Thus, interspecific crosses involving domesticated crops and their wild salt-tolerant relatives have the potential to create increased genetic variability that may prove extremely useful in future biosaline production.

9 Genetic Engineering

Salt tolerance is a multigenic trait where responses to salt stress include biochemical reactions at the cellular level as well as whole-plant morphological adjustments. It is still not yet understood how individual genes, and orchestrated combinations thereof, behave within the whole plant's physiological response to salinity. Until now, only a small number of genes have been identified and isolated, and their role in conferring salt-tolerant traits to salt-sensitive crops is still unclear. For many researchers, it is difficult to see how one could "surgically" introduce these genetic traits into plants without the associated biochemical and morphological mechanisms to implement them.

In the future, genetic engineering may offer incremental techniques (pyramiding) for making commercial crops more salt tolerant. Current transgenic approaches typically involve the transfer or introduction of genetic traits in order to enhance a plant's capacity for excluding and/or tolerating excess salts. However, advances in the design of transgenic crops, initially dependent upon the identification of salt-tolerant genes, face a number of further obstacles such as the extremely small size of genes; crude methods to isolate, remove, and transfer them; and our limited ability to regenerate new plants (in vitro) from single cells. As mentioned, the creation of salt-tolerant transgenic plants often involves certain trade-offs, such as lower productivity and yield potential.

One approach to genetically engineering improved salt tolerance involves increasing the levels of protective osmolytes (i.e., proline, trehalose, mannitol, and glycine betaine) and active solutes within the cytoplasm that mitigate the effects of abiotic stresses (i.e., salt, water, and heat/cold). Another transgenic approach focuses on the manipulation or "overexpression" of genes that regulate intracellular transfers and salt accumulation within the cell sap. A recent development at the Universities of California and Toronto, which has attracted considerable attention, involves the insertion of genes from cressweed (*Arabidopsis thaliana*) into rapeseed and tomato plants, enabling them to accommodate higher salt concentrations (vacuole sequestration) in their cells and tissue while maintaining normal leaf, seed, and fruit production.

10 Challenges and Future Prospects

There is a need to search for means to improve salt-affected soils so that such soils could support highly productive and meaningful land-use systems to meet the current challenges of global food security. In addition, the crop adaptability to salt-stress conditions should also be improved. It is important to shape the composition of coastal plant communities, but our knowledge about how different species respond physiologically to variable salinity levels is limited. Our understanding of physiological/biochemical mechanisms underlying halophytes under variable salinities is very scarce. Therefore, the physiological and molecular studies to reveal the underlying mechanisms of these processes are important. Additionally, discovering the induction of signaling cascades leading to profound changes in specific gene expression is also considered an important salt-stress adaptation. Molecular knowledge of response and tolerance mechanisms will pave the way for engineered plants that can tolerate salt stress and could be the basis for production of crops which can result in economic yield under salt-stress conditions.

Phytoremediation of saline soils has been studied by researchers in the recent past, and it was observed that the use of some halophytes could remove salt from soil. There are certain limitations that must be overcome for this plant-based remediation system to come into common usage. Phytoremediation can be time-consuming because it requires several growing seasons to lower the level of contaminants in soil. It is also limited to soil depths that are in the rooting zone. It is necessary to find that the plants having the capability to remove the maximum quantity of salts by producing higher biomass with some economic importance are mainly selected for phytoremediation and the selected plant species should tolerate high salt concentration.

The forthcoming challenge for using halophytes to remediate soil salinity is to develop a plant with diverse salt-accumulating capacity in a cost-effective way. Identification of novel genes with high biomass yield characteristics and the subsequent development of transgenic plants with superior remediation features would be crucial for such type of research.

Another disadvantage of phytoremediation is that it reduces sodicity more slowly than chemical approaches and requires calcite to be present in the soil. In addition, the usefulness of phytoremediation is limited when soil is highly sodic, as this is likely to result in the phytoremediation of crop's growth being variable and patchy. Under these conditions, the use of chemical amendments such as gypsum is inevitable. Recent trends suggest that the use of sodic soils for crop production systems will increase in the future. Therefore, an assessment of the impact such use will have on the environment and crop productivity will inevitably have to be made. We need to be aware, therefore, that we cannot simply evaluate the amelioration techniques used solely according to the impact that they have on soil sodicity levels. In order to take a holistic approach, the sustainability of the different soil amelioration methods must also be evaluated. In fact, such an approach must consider the economic, social, and environmental aspects of an amelioration technique. The development of successful agriculture on these soils will require a greater understanding of the potential of plant species to withstand ambient salinity and sodicity levels in soil and water and also of the uses and markets for the agricultural products produced.

Within the past decade, progress with molecular markers and quantitative trait loci (QTL) has allowed scientists to map and tag genetic traits associated with salt tolerance at the cellular level. Traditional breeding and biotechnology programs are now being accelerated by the use of molecular markers that indicate the presence of salt-tolerant traits without the necessity of laborious and time-consuming screening procedures. Ultimately, these traits must prove to be inheritable and sustainable over many generations. Continued efforts in the identification and description of stress-tolerant taxa and physiological and molecular studies to understand their tolerance mechanisms are therefore justified. Identification of regulatory genes and transcription factors involved in stress-inducible expression of osmoprotectant biosynthetic pathways is also of great interest. Tools like vectors for multiple gene transfer, stress-inducible promoters, and efficient selectable markers need to be developed and evaluated. The gene products involved in ion homeostasis have been identified by the use of yeast model systems and by analyzing mutants altered for salt sensitivity. There are large numbers of specific proteins reported in various genera of plant growth-promoting rhizobacteria (PGPR) that showed increase in their level of expression upon adverse conditions such as salt. In a postgenomic era, proteomics is one of the best strategies used to reveal the dynamic expressions of whole proteins in cells and their interactions.

11 Microbial Bioremediation

Utilization of microorganisms to metabolically mediate desired chemical reactions or physical processes is a useful general definition of bioremediation (Skladany and Metting 1993). The use of selected symbiotic soil microorganisms to enhance plant growth, widely practised for some organisms and widely researched for others, fits at one end of the spectrum encompassed by this definition. These organisms include mycorrhizal fungi, *Rhizobium* and *Frankia*, each of which can enhance plant growth by increasing the supply of growth-limiting nutrients.

Bioremediation has been proposed as an economical, sustainable, effective, and environmentally friendly alternative to conventional remediation technologies. Bioremediation is an expanding area of environmental biotechnology and may simply be considered to be the application of biological processes to the treatment of pollution. The metabolic versatility of microorganisms underpins practically all bioremediation applications, and most work to date has concentrated on organic pollutants, although the range of substances which can be transformed or detoxified by microorganisms includes solid and liquid wastes, natural materials, and inorganic pollutants such as toxic metals and metalloids.

12 Recent Trends in Soil Bioremediation

There are more than 3,000,000 contaminated sites worldwide continuously posing threat to the health and well-being of human being and the environment (Singh and Naidu 2012). These contaminated sites also represent a case of lost economic opportunity (Gillespie and Philp 2013). About half a century ago, the contamination of sites was started to be reported and the number has continuously increased year after year. Moreover only a tenth of contaminated sites have been known to be remediated as removal of the contaminants once released in the environment is challenging (Singh and Naidu 2012). This contamination poses serious threat to land resources affecting the food security and groundwater contamination. Today, cleanup of these contaminated sites is a need of the hour. Physical and chemical remediation, digging-dumping, and incineration are among the common approaches being used for the removal of the contaminants from the environment (Tripathi et al. 2015).

Bioremediation, the application of science and engineering based on plants and microorganisms to analyze and solve problems, can offer an effective alternative for the remediation of contaminated sites. In recent years, bioremediation has been constantly developing and gained popularity in order to become an effective and reliable technique for remediation of contaminated sites. Currently bioremediation is gaining popularity and social acceptance over the other technologies for remediation of contaminated sites as it is cost effective and environment friendly in nature (Rayu et al. 2012). Three main approaches of bioremediation include use of microbes, plants, and enzymatic processes (Tripathi et al. 2015). All three approaches have been used with some success but are limited by various confounding factors. The latter is because of low competitiveness and adaptability of the microbial inocula, inappropriate inoculation procedures, reduced bioavailability, and higher toxicity of the pollutants toward plants and microbes (Rayu et al. 2012). This often leads to slow and incomplete transformation. The emerging technologies have the potential to overcome these problems and revolutionize the microbial, enzymatic, and plant-based bioremediation approaches (Bell et al. 2014). The omics revolution of the past decade has increased our understanding of microbial life and plant metabolism and some of the conditions that enhance the performance of plants and microbes in contaminated soils and other environmental compartments. Combinations of omics tools and new bioinformatics approaches will further improve our understanding of integrated activity patterns between plants and microbes and determine how this association can be modified to enhance the plant biomass, appropriate assembly of microbial communities, and, ultimately, the bioremediation activity.

13 Emerging Sustainable Approaches for Bioremediation

Low-cost biotechnological inputs are making the process of bioremediation more popular and acceptable. For example, agriculture waste material rich in organic matter could also be used for enhancing the microbial activity at contaminated sites helping in waste management and making the remediation process faster. Also use of indigenous microorganisms and plants offers better solution as they already have the ability to survive in the particular contaminated environment. A novel remediation technology has been proposed which offers solution for the cleanup of mixed or multiple pollutant contaminated sites. This technology utilizes the ability of plants and rhizospheric and endospheric microorganisms altogether. Pollutants are first degraded in the rhizosphere by competent rhizospheric microorganisms. The pollutant that is taken up by the plant is degraded by the endophytic microorganisms. Apart from the removal of the pollutant from the environment, bioremediation offers additional benefits like carbon sequestration (Tripathi et al. 2015). Now the focus has been shifted to generate bioeconomy through bioremediation. The biomass harvested after bioremediation could be used for biofuel production. Also if proper monitoring and certification are done, low contaminated sites could be used for food fodder and fiber production.

14 Use of Endophytic Microorganisms

Endophytes are the microorganisms that thrive inside the plants. They face less competition for nutrients and are more protected from adverse changes in the environment than bacteria in the rhizosphere and phyllosphere as they interact closely with the host plant (Weyens et al. 2009). They can help in degradation of the pollutants taken by the plants, thus lowering the phytotoxicity. From the leaves of dominant halophyte plant species dominant in coastal ecosystem of west coast of India, halophilic endophytic bacteria were isolated and assessed their plant growth promotion (Arora et al. 2014a). Recent evidence indicates that endophytes can contribute to phytoremediation of recalcitrant organic compounds and heavy metals (Thijs et al. 2014; Becerra-Castro et al. 2013). Endophytic bacteria can positively enhance plant growth either (1) directly through production of phytohormones (auxins and cytokinins) or by increasing the amounts of available nutrients by a number of biochemical processes (e.g., N_2-fixation, phosphate solubilization, siderophore release increasing Fe availability) or (2) indirectly through the suppression of ethylene production by 1-aminocyclopropane-1-carboxylic acid deaminase (ACCD), through chemical induction of plant defense mechanisms, or by the degradation of harmful contaminants (Thijs et al. 2014; Weyens et al. 2009). These properties of endophytic microorganisms make them suitable candidate for application in phytoremediation in salt and drought stress as well as organic pollutants in soil and enhancing the phyto-uptake of heavy metals.

15 Effects of Salt on Soil Microorganisms

Soluble ion concentrations (especially sodium ion) greater than about $0.15\,M$ ions in soil lead to hyperosmotic conditions which force water to diffuse out of a microbial cell. The cells will then shrink or plasmolyze. In addition, the high sodium ion concentration also causes the water associated with such solutes to become unavailable to microorganisms. Basically, the effect of sodium ion on the growth of microorganisms of different species will differ due to growing water activity of each microorganism. Microorganisms under hypertonic environments (low water activity) either die or remain dormant except halotolerant and halophilic microorganisms that can combat this problem. Generally, high soil salinity can interfere with the growth and activity of soil microbes; hence, it indirectly affects the nutrient availability to plants. Therefore, the study of interaction between soil microorganisms and plant is needed.

16 Adaptation of Halophilic Bacteria in Response to High Osmotic Pressure

Availability of water is the most important prerequisite for the life of any living cell. The ability of an organism to adapt to changes in external osmotic pressure (osmoadaptation) and the development of mechanisms to achieve this (osmoregulation) are fundamental to its survival (Csonka 1989). In general, exposure of microorganisms to hypersaline environments triggers rapid fluxes of cell water along the osmotic gradient out of the cell. This causes a reduction in turgor and dehydration of the cytoplasm and is consequently lethal. Halophilic bacteria have adapted during evolution (genotypic and phenotypic adaptation) to optimally grow in hypersaline environments. Therefore they are not stressed by these conditions (Imhoff 1993). Their adaptation is genotypical while halotolerants adapt phenotypically (Russell 1989). The degree of salt dependency and salt tolerance of microorganisms is distinguished by their levels of salt requirement and salt tolerance that reflects the differences in osmoadaptation to hypersaline environments.

There are three mechanisms available for adaptation of halotolerant and halophilic microorganisms to high-osmolarity environments: (1) the recognition of osmotic imbalance by an osmosensor, (2) the accumulation of osmolytes or compatible solutes in response to the imposed pressure difference, and (3) the stabilization of macromolecules under the new intracellular conditions (Roberts 2000). Although it has been known that AM fungi and other rhizosphere microorganisms are able to increase resistance/tolerance to osmotic stressors (Porcel et al. 2012), further studies are still needed to yield a comprehensive analysis of the transfer of this knowledge to natural ecology. This is fundamental because soil and rhizosphere microorganisms are key factors for plant survival under a changing environment where plants are going to be exposed to adversity on the incoming years, as driven by the climatic change (Barea 2015).

17 Applications of Halophilic Bacteria

Halophilic bacteria provide a high potential for biotechnological applications for at least two reasons: (1) their activities in natural environments with regard to their participation in biogeochemical processes of C, N, S, and P, the formation and dissolution of carbonates, the immobilization of phosphate, and the production of growth factors and nutrients (Rodriguez-Valera 1993); and (2) their nutritional requirements are simple. The majority can use a large range of compounds as their sole carbon and energy source. Most of them can grow at high salt concentrations, minimizing the risk of contamination. Moreover, several genetic tools developed for the nonhalophilic bacteria can be applied to the halophiles, and hence their genetic manipulation seems feasible (Ventosa et al. 1998). Several halophilic microorganisms are being exploited in biotechnology. In some cases, such as the production of ectoine, the product is directly related to the halophilic behavior of the producing microorganism. In other cases, such as the extraction of beta-carotene from *Dunaliella* or the potential use of *Haloferax* species for the production of poly-beta-hydroxyalkanoate or extracellular polysaccharides, similar products can be obtained from non-halophiles, but halophilic microorganisms may present advantages over the use of nonhalophilic counterparts (Oren 2002).

The application of halophilic bacteria in environmental biotechnology is possible for (1) the recovery of saline soil, (2) the decontamination of saline or alkaline industrial wastewater, and (3) the degradation of toxic compounds in hypersaline environments.

The use of halophilic bacteria in the recovery of saline soils is covered by the following hypotheses. The first hypothesis is that microbial activities in saline soil may favor the growth of plants resistant to soil salinity. The second hypothesis is based on the utilization of these bacteria as bio-indicators in saline wells. Indicator microorganisms can be selected by their abilities to grow at different salt concentrations.

Another hypothesis is the application of halophilic bacterium genes using a genetic manipulation technique to assist wild-type plants to adapt to grow in saline soil by giving them the genes for crucial enzymes that are taken from halophiles. The production of genetically modified plants has however been controversial.

18 PGPR for Bioremediation

The term plant growth-promoting rhizobacteria (PGPR) was coined over three decades ago; they are nonpathogenic, strongly root-colonizing bacteria on the surface of plant's roots which increase plant's yield by one or more mechanisms (Babalola 2010). Plant growth-promoting rhizobacteria can affect plant growth by different direct and indirect mechanisms (Glick 1995). PGPR influence direct growth promotion of plants by fixing atmospheric nitrogen, solubilizing insoluble phosphates, secreting hormones such as IAA, GAs, and Kinetins besides ACC deaminase production, which helps in regulation of ethylene (Glick et al. 1999, 2007). Induced systemic resistance, antibiosis, competition for nutrients, parasitism, and production of metabolites (hydrogen cyanide, siderophores) suppressive to deleterious rhizobacteria are some of the mechanisms that indirectly benefit plant growth. According to Vessey (2003), numerous species of soil bacteria which flourish in the rhizosphere of plants, but which may grow in, on, or around plant tissues, and stimulate plant growth by a plethora of mechanisms are collectively known as PGPR.

Soil bacteria are very important in biogeochemical cycles and have been used for crop production for decades. Plant bacterial interactions in the rhizosphere are the determinants of plant health and soil fertility (Vivekanandan et al. 2015). Interaction of plant growth-promoting rhizobacteria (PGPR) with host plants is an intricate and interdependent relationship involving not only the two partners but other biotic and abiotic factors of the rhizosphere region (Dutta and Podile 2010). Plant growth-promoting rhizobacteria bacteria are free-living soil bacteria that can either directly or indirectly facilitate rooting (Mayak et al. 1999) and growth of plants (Glick 1995). Generally, about 2–5 % of rhizosphere bacteria are PGPR (Antoun and Prevost 2005). PGPRs are the potential tools for sustainable agriculture and trend for the future. One of the mechanisms by which bacteria are adsorbed onto soil particles is by simple ion exchange, and a soil is said to be naturally fertile when the soil organisms are releasing inorganic nutrients from the organic reserves at a rate sufficient to sustain rapid plant growth.

The use of PGPR as inoculums in agriculture to alleviate salt stress is the most promising approach to enhance production and yield in salinity-affected regions (Arora et al. 2013). These PGPRs tolerate a wide range of salt stress and enable plants to withstand salinity by hydraulic conductance, osmotic accumulation, sequestering toxic Na^+ ions, maintaining the higher osmotic conductance, and photosynthetic activities (Dodd and Perez-Alfocea 2012). The bacteria obtained from saline environment (Moral et al. 1988) include *Flavobacterium*, *Azospirillum*, *Alcaligenes*, *Acinetobacterium*, and *Pseudomonas* (Rodriguez-Valera et al. 1985; Reinhold et al. 1987; Moral et al. 1988; Ilyas et al. 2012); *Sporosarcina* and *Planococcus* (Ventosa et al. 1983), *Bacillus* (Upadhyay et al. 2009); and *Thalassobacillus*, *Halomonas*, *Brevibacterium*, *Oceanobacillus*, *Terribacillus*, *Enterobacter*, *Halobacillus*, *Staphylococcus*, and *Virgibacillus* (Roohi et al. 2012). Halophilic bacteria strains CSSRO2 (*Planococcus maritimus*) and CSSRY1 (*Nesterenkonia alba*) having plant growth promotion properties were isolated from rhizosphere of dominant halophytes from coastal ecosystem (Arora et al. 2012a, b). Salt-tolerant *Rhizobium* species were isolated from coastal saline soils (Trivedi and Arora 2013).

Ethylene is the plant growth-regulating hormone produced in response to waterlogging (Grichko and Glick 2001), salinity, and/or drought (Kausar and Shahzad 2006; Nadeem et al. 2007; Zahir et al. 2007). PGPRs from stressed environment exhibit 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity (Glick et al. 1998; Arshad et al. 2007) which reduces the level of ACC and endogenous ethylene (Glick et al. 1998; Yuhashi et al. 2000) mitigating the deleterious effects of stress on overall plant growth (Ligero et al. 1991; Hirsch and Fang 1994). The plants inoculated with PGPR having ACC deaminase are relatively more tolerant to environmental stress (Singh and Jha 2015).

The inoculation with halophilic strains of PGPR will help to improve the plant tolerance in stress environment especially salinity and promote their growth particularly in food crops which is essentially required to meet the food demands of the country.

Plant growth-promoting rhizobacteria assist in diminishing the accumulation of ethylene levels and reestablish a healthy root system needed to cope with environmental stress. The primary mechanism includes the destruction of ethylene via enzyme ACC deaminase. There are a number of publications (Ghosh et al. 2003; Govindasamy et al. 2008; Duan et al. 2009) mentioning rhizosphere bacteria such as *Achromobacter*, *Azospirillum*, Bacillus, *Enterobacter*, *Pseudomonas*, and *Rhizobium* with ACC deaminase activity. Most of the studies have demonstrated the production of ACC deaminase gene in the plants treated with PGPR under environmental stress. Grichko and Glick (2001) inoculated tomato seeds with *Enterobacter cloacae* and *Pseudomonas putida* expressing ACC deaminase activity and registered an increase in plant resistance. Ghosh et al. (2003) recorded ACC deaminase activity in three *Bacillus* species, namely, *Bacillus circulans* DUC1, *Bacillus firmus* DUC2, and *Bacillus globisporus* DUC3, that stimulated root elongation in *Brassica campestris*. Mayak et al. (2004) observed tomato plants inoculated with the bacterium *Achromobacter piechaudii* under water and saline stress conditions and reported a significant increase in fresh and dry weight of inoculated plants.

Researchers have demonstrated the feasibility of *Azospirillum* inoculation to mitigate negative effects of NaCl on plant growth parameters. This beneficial effect of *Azospirillum* inoculation was previously observed in wheat (*Triticum aestivum* cv. 'Buck Ombú') seeds, where a mitigating effect of salt stress was also evident (Creus et al. 1997). *Azospirillum*-inoculated wheat (*T. aestivum*) seedlings subjected to osmotic stress developed significantly higher coleoptiles, with higher fresh weight and better water status than non-inoculated seedlings (Alvarez et al. 1996; Creus et al. 1998).

19 Cyanobacteria

These are prokaryotic microorganisms capable of fixing nitrogen and carbon. These are usually considered as primary colonizers. Blue-green algae (BGA) can provide 25–30 % N/ha/ season in rice fields (Goyal and Venkataraman 1971; Venkataraman 1981). In addition to nitrogen, BGA enrich soil with extracellular carbohydrates, hormones, and many secondary metabolites and improve soil health. It increases soil porosity and soil water-holding capacity and ameliorates degraded soil due to excessive use of chemical fertilizers and also salt-affected soils (Kaushik and Subhasini 1995). Based on their capacity to tolerate several stress factors like salinity, pH, pesticides, and desiccation (Rath and Adhikary 1995; Padhi et al. 1997; Adhikary and Sahu 2000), eight cyanobacterial species including *Anabaena, Nostoc, Calothrix,* and *Aulosira* were selected for field use in Orissa and coastal areas.

Blue-green algae have also been used to ameliorate sodic soils, because they are able to tolerate high Na levels during wet seasons. However, there is evidence that they are not effective. In a soil column study, for example, Rao and Burns (1991) evaluated the effect of blue-green algae on the dissolution of calcite in a calcareous sodic soil (pH1:2:10.3, EC1:2:3.5dSm^{-1}, ESP: 89.7). They found that inoculation with blue-green algae had a negligible effect in terms of the decrease observed in soil ESP (from 90 to 88), while the application of gypsum significantly decreased soil ESP (from 90 to 43).

20 Plant-Microbiome Interactions for Salt-Stress Alleviation

Diverse types of stress factors, including salinity, drought, nutrient deficits, contamination, diseases and pests, etc., can alter plant-microbe interactions in the rhizosphere. Recent research is evidencing that plant perception of environmental stress cues triggers the activation of signaling molecules, and phytohormones play a key role (Barea 2015). This signal input is followed by a signal processing and finally by a signal output, which enables plants to respond to these environmental constraints. As plants are exposed to multiple stresses simultaneously, appropriate meta-analyses reveal a complex regulation of plant growth and immunity (Dimkpa et al. 2009). Understanding how phytohormones interact in the signaling network is fundamental to learn how plant-microbiome systems thrive and survive in stressed environments. This understanding is relevant to design biotechnological strategies to optimize plant adaptation mechanisms and to improve the ability of soil microbes for stress alleviation in crops (Pozo et al. 2015). Mechanisms involved in plant-microbe interactions under stress situations are poorly understood. However, ongoing research is evidencing the involvement of changes in plant morphology, physiology, transporter activity, and root exudation profiles, changes that can induce the plant to recruit microbes with stress-alleviating capacities, a strategy able to help crop productivity under stress (Zolla et al. 2013).

As stress factors cause detrimental impacts on the functionality/productivity of agricultural systems, the role of rhizosphere microorganisms in helping plants to thrive in adverse conditions is important (Barea et al. 2013). There is a need to analyze how the ability of soil microorganisms for stress alleviation in crops can be improved, by better understanding of plant-microbe interaction based on the already available meta- "omic" and sequencing approaches.

Current research is realizing that plants can structure their root-associated microbial communities, concerning both diversity and functions (Achouak and Haichar 2013; Hirsch et al. 2013). Particularly, Achouak and Haichar (2013) used the stable isotope probing together with fingerprinting approaches as a molecular detection tool to analyze the impact of the plant species on their rhizosphere microbiome. They confirmed the differential impact of each target plant species on the genetic and functional diversity of the plant-associated bacterial communities.

Therefore, such ability of the plants for shaping microbial communities in their rhizospheres appears as a new opportunity for linking structure and function of the root-microbiome related to nutrient supply and plant protection. Carbon compounds and signal molecules from root exudates are the main drivers of plant-specific effects on rhizosphere bacteria and their proteomes. Actually, the identity and quality of rhizodeposits vary from plant to plant, thereby attracting a specific set of bacteria to the rhizosphere and providing them with a selective pressure to stimulate bacteria to compete and persist (Hirsch et al. 2013), a property which is depending on plant age (Spence and Bais 2013).

According to Bakker et al. (2012), there are two main strategies for manipulating the plant to recruit beneficial microorganisms in its rhizosphere; both of them are based on plant breeding and are addressed to foster beneficial microbial services for improving agricultural developments. One of these alternate paths relies on develop plants able to shape their microbiome by targeting particular taxa for specific functions, i.e., N_2-fixation, P-mobilization, biocontrol, etc. The other approach is based on develop plants able to shape their microbiome for broad characteristics related to promotion of plant growth and health. All in all, in the nearest future, it appears that the more feasible approach to enhance beneficial microbial services in agriculture is the direct manipulation of the soil microbiome. Particularly, a target aim is to reconstruct a minimal rhizosphere microbiome able to provide a maximized benefit to a plant at a minimal photosynthetic cost (Raaijmakers 2015).

A challenging strategy which offers opportunities to enable plants to recruit microorganisms targeted for specific functions is that aimed at engineering nitrogen-fixing cereals (Rogers and Oldroyd 2014; Oldroyd and Dixon 2014; Venkateshwaran 2015).

Future studies have to be undertaken to find specific metabolite-plant species-microbe combinations. Deciphering the biotic and abiotic plant factors that shape the plant-associated microbiome through biasing the rhizosphere offers many challenges that current research is trying to envisage. According to Savka et al. (2013), future work on plants must focus on reprogramming transport functions, while those on microorganisms have to focus on the uptake secreted nutrients and the time course changes in the microbial community structure. A combination of all of these approaches can improve our understanding on how to enhance the competitiveness and persistence of bacteria in the biased rhizosphere to finally improve plant health and agroecosystem productivity.

21 Rhizosphere Engineering: A Futuristic Approach

Diverse research approaches are currently addressed trying to ascertain whether the rhizosphere can be engineered to encourage beneficial organisms, while prevent presence of pathogens. The related research topics offer many challenges because there are many gaps in our understanding on the ad hoc research strategies. Undoubtedly, getting biased rhizosphere opens new opportunities for future agricultural developments based in exploiting the beneficial microbial services to reduce the inputs of agrochemicals thereby reaching sustainable environmental and economical goals.

22 Microbial Consortia

Combined inoculations of rhizobacterial species as consortia to improve the quality of soil also seemed to be a potent area of research in present-day agriculture. Despite progress in research on mixed inoculants, microbial inoculants with multiple organisms are not yet produced commercially. Until now, the research on mixed microbial inoculation was only confined to the development and inoculation of each bacterium in separate formulation. But developments of new inoculant formulation like polymer-entrapped desiccated inoculants have opened new vistas in mixed microbial inoculants. In this direction, the concept of "microbial consortium" assumes greater importance for sustainable agriculture. A group of microbial species work together to carry out an overall reaction or process, in our case beneficial organisms that together help in promoting plant growth. The development of microbial consortium may minimize cost, labor, and energy involved in production of inoculants. It was observed that consortia of halophilic strains of N-fixers and phosphate solubilizers prepared as liquid bioformulation were effective in remediating saline soils enhancing the crop growth and yield of maize and wheat (Arora et al. 2013) under salt stress.

22.1 Application of Microbial Inoculants

For a successful application of microbial inoculants in agriculture, we need to implement the following aspects: (a) To increase the scientific/technological bases of inoculum production and application(b) To generate specific normative for each inoculant type and its application, either on the seeds or on the soil, or to the plant to be transplanted already micronized (c) To establish quality control protocols (d) To minimize the variability of the field results (e) To increase knowledge and dissemination by explicating advantages and limitations and benefits for society

The research on implementing proper delivery of PGPR is needed (Bashan et al. 2014), and other priorities include in-depth evaluation of carriers, an improvement survival of microorganisms in the inoculants, to enhance shelf life of the inoculant product; to use multi-strain inoculants; to implement polymeric/encapsulated formulations; to follow low-cost technology, using local strains; to practice nursery inoculation for transplanted crops; etc. Several companies worldwide are producing PGPR inoculum products (Ravensberg 2015; Kamilova et al. 2015).

Apart from microbial inoculation, there are other challenging opportunities to exploit the beneficial activities of soil microorganisms. The perspectives for the successful manipulation of naturally existing microbial population, toward a sustainable production of healthy foods, are becoming feasible thanks to recent advances in the new system-based strategies to study plant-microbiome interactions.

Particularly, understanding of these interactions is being facilitated by the already available, culture-independent, molecular techniques. These techniques, based on molecular approaches, are also fundamental to evaluate the impacts of perturbations provoked by biotic and abiotic stress factors on soil microbiome diversity and on plant-microbe interactions, in the current scenario of global change.

Diverse approaches are currently used to understand the molecular basis of interactions among plants and microbial communities in the rhizosphere. A basic concept is that plant-specific rhizodeposition (carbon containing materials of plant origin), including root exudation, drives the selection of microbial diversity that the target plant recruits in its rhizosphere (Hirsch et al. 2013). Since the root-associated microorganisms, stimulated by rhizodeposition, carry out specific activities impacting on plant nutrition and health, a feedback loop between plants and microorganisms is generated (Zancarini et al. 2013).

23 Future Challenges for Soil Bioremediation

Some of the recent investigations on PGPR induction of saline tolerance in plants are no doubt promising, but still more work is needed on the following: (1) In most of the studies, only NaCl salinity has been used. But in reality, soil salinity/sodicity is caused by a combination of several salts like Ca and Mg salts in saline soils and carbonates and bicarbonates of Na in sodic soils. (2) Therefore, there is a need to perform studies using artificial salt solutions in all in vitro assays. (3) The paradigms of applicability of these beneficial bacteria in different agroecosystems may be tried directly in saline soil employing the most popular crops in the locality. (4) Further research on understanding the mechanisms of PGPR-mediated phytostimulation may pave way to find out more competent rhizobacterial strains to work under diverse agroecosystems. (5) Studies on induction of salt tolerance in many popular vegetable crops such as tomato (*Lycopersicon esculentum)*, okra (*Abelmoschus esculentus*), and leafy, root, and tuberous vegetables employing PGPR are very much needed. This would also facilitate marginal farmers to raise vegetables for household purposes in the salt-affected soil in and around their locality.

One of the recent focuses of research involves implication of PGPR to combat salt stress. The development of biological products based on beneficial microorganisms can extend the range of options for maintaining the healthy yield of crops in saline habitat. In recent years, a new approach has been developed to alleviate salt stress in plants, by treating crop seeds and seedlings with PGPR. The great opportunity for salt tolerance research now is its ability to be combined with halophilic PGPR.

Generally many achievements have been reached with the application of microbial biotechnology in agriculture in normal as well as salt-stress soils, but many challenges as well as opportunities need to be explored for the future sustainable agricultural developments.

A signaling network orchestrated plant-microbiome interactions needed to thrive and survive in stressed environments. Understanding this signal cross talk is fundamental to design biotechnological strategies to optimize plant adaptation mechanisms and to improve the ability of soil microbes for stress alleviation in crops. Several approaches are currently addressed to ascertain whether the rhizosphere can be engineered (biased) to encourage beneficial organisms.

The bottom line of every inoculation technology is its successful application under agricultural and industrial conditions. The microbial formulation and application technology are crucial for the development of commercial salt-tolerant bioformulation effective under salt-stress conditions. Bioformulations offer an environmentally sustainable approach to increase crop production and health, contributing substantially in making the twenty-first century the age of biotechnology. Apart from bioformulation, reclamation and improving fertility of stressed sites is another aim to be focused on. The promising approach toward tackling the problem of soil salinity utilizing beneficial microorganism(s) including PGPR will make the greatest contribution to the agricultural economy, if inexpensive and easy-to-use stress-tolerant strain formulation(s) could be developed.

Microbial mixtures such as multitasking inoculants and stress-protecting bioformulations are one alternative to overcome inconsistent in vivo effects. It has been observed that inoculation with mixed strains was more consistent than single-strain inoculations. The future possibility for efficient inoculation, valid for plants propagated from tissue culture, is to inoculate the salt-tolerating PGPR into the plant cell suspension and regenerate embryos and eventually stress-tolerating plants. A potentially promising future application could be the enhancement of drought tolerance or salt tolerance of transgenic plants by identification of enzymes and genes involved in the synthesis of novel osmoprotectants found in stress-tolerant microorganisms that can be expected to provide more such opportunities for stress tolerance engineering in agricultural crops.

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