CHAPTER 10

APPROACHES FOR ENHANCING SALT TOLERANCE IN SEED SPICES

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ABSTRACT

India continues to be the world leader in production of seed spices that are used to impart flavor and aroma to the food products. Seed spice crops, extensively grown in arid and semiarid tracts, have to face the compounded impacts of salinity, water scarcity, and climate change. Seed spices are moderately sensitive to salt stress; excess salt concentrations in the root zone often debilitate crop growth resulting in moderate to heavy reductions in economic yield. Salt tolerance of a plant describes its capacity to endure salinity stress without appreciable reductions in plant growth and yield. An understanding of the physiological mechanisms, morphological traits, and genetic mechanisms that impart salt tolerance may help develop management practices to maximize crop output under saline conditions. This chapter describes several conventional and improved techniques for salinity management in seed spices. Beginning with the selection of salt-tolerant planting material, the role of different techniques such as seed priming, nutrient management, microbial inoculants, plant growth regulators, and bio-stimulants in mitigating the salt hazard is discussed. It is concluded that a well thought out ensemble of agronomic manipulations can help realize high seed spice yields in salty soils.

10.1 INTRODUCTION

Seed spices comprise of a wide variety of plants that produce volatile and nonvolatile food additives. They are used to impart flavor and taste to the food and also for their health promoting benefits.[64] Seed spices have also been traditionally used as preservatives, colorants, and flavor enhancers. In many countries, they are used as the ingredients of traditional medicine. Both *in vitro* and *in vivo* studies have also revealed their antioxidant, digestion stimulant, antibacterial, antiinflammatory, antiviral, and anticarcinogenic activities.[113] In India, out of 63 spices grown in different parts, 20 are classified as seed spices with cumin (*Cuminum cyminum* L.), coriander (*Coriandrum sativum* L.), fenugreek (*Trigonella foenum-graecum* L., *Trigonella corniculata* L.), and fennel (*Foeniculum vulgare* Mill) being cultivated in a sizeable area. Similarly, celery (*Apium graveolens* L.), nigella (*Nigella sativa* L.), dill (*Anethum graveolens* L., *Anethum sowa* Kurz), ajwain (*Trachyspermum ammi* Sprague), anise (*Pimpenella anisum* L.), and caraway (*Carum carvi* L.) are the minor seed spices grown in India and other parts of the world (Table 10.1).

TABLE 10.1 Important Seed Spices Cultivated in Different Parts of the World.

English name	Hindi name	Botanical name
Aniseed	Vilayati sounf	*Pimpinella anisum* L.
Caraway	Shahi jeera	*Carum carvi* L.
Carom seed	Ajwain	*Trachyspermum ammi* L.
Celery	Ajmoda	*Apium graveolens* L.
Coriander	Dhania	*Coriandrum sativum* L.
Cumin	Jeera	*Cuminum cyminum* L.
Dill	Sowa	*Anethum graveolens* L.
Fennel	Saunf	*Foeniculum vulgare* Mill.
Fenugreek	Methi	*Trigonella foenum-graecum* L.
Nigella	Kalaunji	*Nigella sativa* L.

Note: The English names given here are used throughout the text except in case of Carom seed for which the Hindi name *Ajwain* is used. For the minor crops not mentioned here, English names along with botanical name (only at the first mention) are given.

Most of the major seed spices included in this chapter are native to the land regions in vicinity of the Mediterranean Sea. Similarly, most of them are umbelliferous plants (i.e., aromatic flowering plants) belonging to the family Apiaceae with the exception of fenugreek (family Fabaceae) and nigella (family Ranunculaceae). In India, five major seed spices (i.e., cumin, coriander, fennel, fenugreek, and carom) occupy an area of about 1.45 million hectare (M ha) with total production of about 1.0 million tons (MT) and productivity of about 0.9 t ha^{-1}.[81] Historically, India has always been recognized as the "land of spices" and continues to be their largest producer, exporter and consumer in the world. Besides India, other major seed spice producers are Iran, Turkey, Egypt, Morocco, Canada, Pakistan, Romania, Soviet Union, Israel, China, Burma, and Thailand.

In India, Rajasthan and Gujarat states are known as the "Seed Spices Bowl" together contributing to more than 80% of the total seed spices produced in India. Other states where seed spices are commonly grown are Bihar, West Bengal, Uttar Pradesh, Madhya Pradesh, Odisha, Punjab, Karnataka, and Tamil Nadu. Over the years, the global demand for Indian spices has consistently increased so that exports were increased by about 29% in coriander, 70% in cumin, 3.1% in celery, 58% in fennel, 49% in fenugreek, and 97% in others with an overall increase of 62% in the recent past. Despite significant surge in the export volume in recent years, there is still a huge demand for Indian seed spices in the global market.[96] The growing predominance of India in global seed spice industry is evident by the fact that out of total global demand of seed spices (>100 thousand tons) about 60% are supplied by India alone.

Salinity is a major environmental stress that reduces soil's capability to produce food. As a generic term, salinity is used to refer to soils containing either excess soluble salts (i.e., saline) or excess exchangeable Na^+ (sodic) or both (saline-sodic). Often, saline and sodic soils are also underlain with marginal quality saline or sodic ground water unfit for irrigation. Predominance of excess soluble salts raises the saturation paste salinity of soil (EC_e > 4 dS m^{-1}) leading to osmotic stress and specific ion toxicities (Na^+ and Cl^-) in plants.

In sodic soils, more than 15% of the exchange sites are occupied by Na^+ ions giving rise to high exchangeable sodium percentage (ESP > 15) conditions leading to soil structure loss and poor water transmission through the soil profile. Globally, the problem of salinization is especially severe in arid and semiarid regions of the world where faulty and over irrigation coupled with the neglect of land drainage are major drivers of excessive salt accumulation in the crop root zone. On the contrary, salinization of agricultural lands in dry and rain-fed regions is primarily ascribed to the removal of perennial vegetation to grow the annual crops. Problems of irrigation-induced as well as dry land salinities arise largely due to inappropriate anthropogenic interventions and unscientific land management to augment the crop productivity at the expense of soil and environmental quality.[102]

Traces of soluble salts and harmful ions such as Na^+ are naturally found in almost all cultivated soils. In some regions of the world, certain natural factors result in the excessive concentration of such geogenic salts; and this condition is referred to as primary salinity. However, in most of the cases, primary salinity affected lands remain in a manageable condition and pose limited constraints to crop production. In contrast as previously mentioned, unscientific on-farm water management often leads to secondary soil salinity characterized by heavy salt accumulation and subsoil waterlogging. Currently, over 800 M ha of global agricultural land are affected by primary salinity. In addition, human-induced secondary salinization affects the productivity of about 77 M ha of world's crop lands. Of the total secondary salinity affected area, about 45.4 M ha are in irrigated commands of arid regions and the rest are distributed in rain-fed areas.[124] In India, salt-affected soils cover approximately 6.73 M ha area which is projected to increase to 16.20 M ha by 2050 pointing to the fact that rate of salinization will surpass the reclamation efforts.[53]

Besides salt-induced land degradation, several other factors such as population growth, urban and industrial expansion and pervasive land use have, over time, led to reduced availability of productive lands for crop production. Fresh water, a key input in agricultural production, is not only becoming a scarce resource but the problem of poor quality water has also significantly increased in the last few decades. Climate change impacts are likely to further reduce the availability and/or quality of land and fresh water for agriculture in the coming decades necessitating agricultural expansion into marginal environments.[102] In so far as salt affected lands are concerned, a suit of measures can be successfully employed to harness their productivity.

This chapter discusses the response of seed spices to salt stress, various adverse effects of salinity on plant physiological relations and productivity of these crops. Besides, this chapter also discusses some conventional and the advanced techniques of salinity management in seed spices to augment the productivity under saline conditions.

10.2 PLANT RESPONSES TO SALT STRESS

A majority of the cultivated crops, referred to as glycophytes, are sensitive to salinity and fail to survive when salt concentration exceeds the threshold value. In contrast, plants which not only profusely grow but also produce viable economic yields in hyper-saline environments are described as halophytes. One of the basic differences between halophyte and glycophytes is that halophytes have the ability to survive under severe salt shock[87] by modulating the physiological activities at cellular, tissue and whole plant levels. Apparently, a plant is adjudged to be salt tolerant if it exhibits the ability to withstand high salt concentrations in the root zone without any appreciable reduction in the plant growth and yield.[101]

Under high salinity conditions, salt-induced hyper-ionic and hyperosmotic effects often severely affect the plant growth and in certain cases may result in complete crop loss; especially in salt sensitive genotypes. Adverse effects of salinity are often severe in arid regions compared to both semiarid and humid climates apparently due to scanty rainfall and very high evapotranspiration demand in arid zones. Poor soil and water management practices often accentuate salt stress to the levels that crop production virtually becomes impossible in salt affected arid lands.[35] A set of factors including high osmotic stress due to low soil water potential, Na^+ and/or Cl^- toxicities and imbalanced nutrition account for most of the adverse effects on plant growth under saline conditions.

Elevated salt levels raise the osmotic pressure of the soil solution and create the physiological drought, that is, though water remains available, plants fail to extract it from the soil.[77,102] Nutritional imbalance and specific ion effects are mainly due to high accumulation of Na^+ and Cl^- hampering the availability of other essential elements like K^+, Ca^+, NO_3^- or P that in turn affects the activities of key enzymes.[13]

10.2.1 MECHANISMS OF SALINITY TOLERANCE

Salt tolerance describes the ability of plants to endure salinity stress without any appreciable reductions in growth, yield, and produce quality. Different morphological, physiological, and genetic mechanisms contribute to salt tolerance. For example at the cellular level, salt tolerance depends on the ability of growing plant cells either to exclude the toxic ions or an increased tolerance to minimize the adverse effects on cellular processes. Some of such mechanisms are briefly summarized in this section.

10.2.1.1 OSMOTIC ADJUSTMENT

Generally, osmotic stress suppresses the plant growth in salt-stressed plants regardless of their capacity to exclude the salt. Partitioning of salt from the cytoplasm into the vacuole creates a strong osmotic gradient across the vacuolar membrane. Salinized plants tend to balance this gradient by increasing accumulation of solute molecules in the cytoplasm, a process known as osmotic adjustment,[68] which helps the plants to adapt to salinity by maintaining the cell turgor and volume. Different kinds of compatible solutes have been identified from the plants exposed to salinity. They exhibit more or less similar properties including a low polar charge, high solubility, and large hydration shell.[84] Besides maintaining the cell turgor, compatible solutes are also implicated in stabilizing the active conformation of cytoplasmic enzymes and thus protecting them against inactivation by inorganic ions.[105] Compatible solutes include compounds such as proline, glycine-betaine, and other related quaternary ammonium compounds, pinitol, mannitol, and sorbitol. Notwithstanding the advantages offered by such cell benign molecules, their adequate production comes at the cost of metabolic expense as plants have to spend a significant portion of energy otherwise to be used to support the active growth.[46] As a consequence, plants tend to accumulate high amounts of inorganic ion from the growing substrate to prevent the energy expenditure as comparatively far lesser energy is required for the osmotic adjustment through inorganic ions than that conferred by organic molecules synthesized in the cell.[116] Excessive ion accumulation, however, tends to debilitate the plants by altering the vital cell processes.[47]

10.2.1.2 SALT INCLUSION VERSUS EXCLUSION

Most of the glycophytes fail to utilize the salt transported to the leaves from the root leading to progressive increase in salt concentration, slower growth and the eventual leaf death. The genotypes having ability to exclude the salt, even partially, exhibit greater salt tolerance than those lacking this mechanism. Compared to the glycophytes, vast majority of halophytes employ salt inclusion as a strategy to achieve osmotic balance with the external medium.[111]

10.2.1.3 Na^+/K^+ DISCRIMINATION

Besides salt exclusion, selective ion uptake from the growing medium greatly affects the ability of plants to withstand the salt damage. Salt tolerant genotypes often show the preferential accumulation of K^+ over Na^+. Such genotypes possess the ability to discriminate Na^+ from K^+ and thus succeed in substituting Na^+ for K^+ for root uptake.[97] Maintenance of adequate levels of K^+ in the young expanding tissues is often linked to salt tolerance even in salt sensitive genotypes.[106]

10.3 RESPONSES OF SEED SPICES TO SALINITY

The adverse effects of salt on plant growth and development vary with the magnitude and duration of salinity as well as the crop growth stage. Owing to the complexity of the trait, the genetic and physiological bases of salt tolerance are not yet fully understood in most of the crop plants. Often, several genes controlling salinity tolerance in a given plant species interact strongly with environmental factors. It is due to this reason that genetic variation can only be demonstrated indirectly by measuring the responses of different genotypes. In practice, measurements on growth parameters and economic yield are widely used to estimate the plant response to salinity, especially at moderate salinities. In most of the annual crops, salt-induced reduction in biomass production (which usually directly correlates with the yield) compared with the control plants over a period of time is considered to be a reliable estimate of the relative impact of salinity on different crops/genotypes. Similarly, in many perennial crops, percent reduction in plant survival is often adjudged to be a good indicator of salt-induced damage.[76,77,102] Different effects of salinity on physiological activities, metabolism, growth, and economic yield in seed spices are presented in this section.

10.3.1 PLANT PHYSIOLOGY UNDER SALINE CONDITIONS

The detrimental effects of salt on plant growth and development are direct result of the changes at cellular level which impact key physiological activities. Initially, soil water deficit caused by the osmotic stress followed by high salt concentrations inside the plant lead to an array of changes in plant metabolism. It then affects seed germination, seedling establishment, biomass production, yield, and quality of the final product.

10.3.1.1 CELL MEMBRANE STABILITY

In most of the glycophytes, reduced availability of CO_2 in chloroplast cells and accumulation of toxic ions such as Cl^- lead to overproduction of reactive oxygen species (ROS) and lipid peroxidation destabilizing the cell membranes. Cell membrane stability (CMS) is a routinely used measure to distinguish the salt tolerant and salt susceptible genotypes in crops as higher CMS seems to confer salt tolerance. Electrolyte leakage (EL) often provides an indirect, but reasonable estimate of the relative CMS under stress conditions.[107] In fenugreek, leaf membrane permeability was gradually increased with addition of NaCl (0, 60, 120, and 180 mM) into irrigation water.[78] Increase in salinity from 0 to 25 mM NaCl led to almost two-fold increase in EL in chili (*Capsicum annuum* L.) plants. At 50 mM NaCl level, plants registered about two-and-half fold increase in EL over control.[98] In salinized fenugreek plants (100 or 200 mM NaCl), membrane permeability, lipid peroxidation and chlorophyll loss eventually caused the leaf senescence.[29] Salt stress induced a noticeable increase in malondialdehyde (MDA: a measure of lipid peroxidation) content in fennel. MDA level was increased by 18% at 50 mM NaCl and 29% at 100 mM NaCl compared with control indicating salt-induced cell membrane damage.[43] Hydrogen peroxide and MDA contents were increased in the leaves of salinized coriander plants.[59]

10.3.1.2 PLANT WATER STATUS

Salt-stressed plants show reduced water uptake and content. The water potential of plants thus decreases with increasing salinity.[47] A genotype exhibiting minimum reductions in leaf turgidity will be better able to support turgor dependent processes such as growth and stomatal activity in stressful environments.[75] To overcome the water shortage, plants undergo osmotic regulation by increasing the negativity of the osmotic potential of the leaf sap. Relative water content (RWC) of a leaf is a commonly used measure of its hydration status (i.e., actual water content) under stress conditions. By providing a measurement of the "water deficit" of the leaf, RWC indicates the degree of stress experienced by the plants. RWC combines the effects of both leaf water potential and osmotic adjustment as an index of plant water status.

Ajwain plants did not show appreciable reduction in RWC up to 4 dS m^{-1} salinity compared to control. However, RWC was declined by about 33% and 40% at 8 and 12 dS m^{-1} salinity levels, respectively, than the control.[66] Salt-induced decrease in plant water consumption suppressed plant biomass production and seed yield of fennel.[99] Fennel cv. RMt-1 showed decline in RWC with increasing salinity (50–200 mM NaCl) levels with the decrease in RWC becoming more severe with the increasing duration of the salt exposure.[58] Lower soil osmotic potential decreased the water uptake by salinized sweet basil (*Ocimum basilicum* L.) plants resulting in marked reductions in growth and biomass production.[92] Water content of seedling tissues was 44.84 and 46.01%, respectively, in cumin and fennel at 10 dS m^{-1} salinity compared to about 53% in the seedlings grown in normal soils in both the crops.[50]

10.3.1.3 LEAF CHLOROPHYLL

Leaf chlorophyll levels (*a*, *b*, and total chlorophyll), in conjunction with other physiological parameters, are frequently assessed to understand the extent of salt injury in plants. Although leaf chlorophyll levels tend to drop in salt-stressed plants, low-to-moderate salinity may sometimes enhance its synthesis in certain genotypes. Again, two types of chlorophyll (*a* and *b*) may be differentially affected by salinity. For example, NaCl stress reduced chlorophyll-*b* but increased chlorophyll-*a* content in summer savory (*Satureja hortensis* L.).[4] Decline in leaf chlorophyll levels under saline conditions is ascribed to the breakdown of chlorophyll pigments and the instability of the pigment-protein complex. Salt ions also interrupt with *de novo* synthesis of structural proteins of the chlorophyll molecule.[54] Nitrogen deficiency, insufficient leaf turgor and increased activity of chlorophylase enzyme also account for the low chlorophyll levels in salinized plants.[3] Salinity-induced changes in leaf chlorophyll levels in seed spices (Table 10.2) indicate that factors such as growing season, degree of salinity and presence of chemicals other than salts also influence the extent of chlorophyll loss.

TABLE 10.2 Salt-induced Changes in Leaf Chlorophyll Concentration in Seed Spices.

Crop	Findings	References
Dill	Total leaf chlorophyll significantly increased in the autumn regardless of salinity. In contrast, in spring, it increased at low salinity (2–4 dS m^{-1}) but decreased at higher salinity (6–8 dS m^{-1})	[109]
Fennel	Salt treatment (50 and 75 mM NaCl) caused significant reductions in fresh and dry weights, and chlorophyll (*a* and *b*) and β-carotene contents in seedlings	[82]
Fenugreek	Saline irrigation (0, 60, 120, and 180 mM NaCl) decreased plant dry matter and chlorophyll production with the highest reductions observed at 180 mM NaCl than control. Application of silicon (0.2 mM Na_2SiO_3) partially mitigated the salt injury	[78]
Nigella	NaCl (150 mM) stressed plants showed decrease in leaf RWC, leaf area and chlorophyll content resulting in the lower P_N and dry matter production. Kinetin (10 μM) spray appreciably reduced most of these adverse effects and upregulated antioxidant enzyme activities leading to higher yield compared to the untreated stressed plants	[100]

10.3.1.4 CARBON ASSIMILATION

Reduced availability of photo-assimilates is one of the major causes of plant growth reduction in saline soils. Depending on plant species, salinity may either decrease the leaf surface area for photosynthesis or may result in a reduced rate of photosynthesis.[108] In so far as decrease in photosynthetic rate is concerned, either stomatal or non-stomatal factors may be responsible.

Reduced stomatal activity, restricted CO_2 diffusion to chloroplast and alterations in photosynthetic metabolism are the stomatal factors which hamper carbon assimilation in salinized plants. Similarly, oxidative stress may also contribute to the lower photosynthetic rate.[22] In general, a decrease in stomatal activity is recognized as a major cause of salt-induced photosynthetic decline in crop plants. Salt stress may also affect the ability of a plant to transport the photo-assimilates to the growing leaves.[114] In saline soils, plants tend to reduce the stomatal conductance (gs) to arrest the transpiration rate (E) for efficient water use as well as reduced salt loading via transpiration stream. The fact that reduced E limits salt loading into the foliage may be an efficient adaptive trait, especially when salt stress lasts only for a limited period of time. Although plants resort to stomatal closure mainly to curtail the water loss, yet it comes at the cost of net photosynthesis (P_N) as CO_2 diffusion to chloroplast cells is substantially lowered.

Stomatal limitations appeared to be responsible for decreased P_N in NaCl stressed (40 and 80 mM) coriander plants as salinity reduced gs, E and internal CO_2 concentration.[28] Low salinity (12.5 mM Na_2SO_4) improved salt and drought tolerance in several accessions of coriander due to decrease in E and the consequent increase in water use efficiency.[18] Despite significant reductions in plant growth and seed yield, increasing NaCl levels (40, 80, 120, and 160 mM) did not affect P_N and E rates indicating a negative correlation between gas exchange parameters and salt tolerance in ajwain.[10] Saline irrigation (10 dS m^{-1}) differentially affected leaf metabolism in cumin genotypes with genotype "UC-198" exhibiting the highest decline (14.8%) in starch concentration followed by "RZ-209" (11.1%), while it was least in the tolerant genotype "RZ-19" probably due to higher reductions in P_N in the former ones.[39]

Low NaCl (25 mM) had negligible effect on carbon assimilation in celery, but intermediate salinity (100 mM NaCl) decreased gs, while high NaCl levels (300 mM) diminished the carboxylation capacity and thus adversely affecting P_N.[32] Although sufficient data are not available to reach to conclusive evidence regarding the gas exchange characteristics in seed spices under salinity, yet it appears that relative impacts of salt on photosynthesis and water use may vary with the agro-climatic conditions, species/genotype as well as the level and duration of salinity.

10.3.1.5 MINERAL UPTAKE AND ASSIMILATION

Plants require different macro- and micronutrients for metabolic activities such as photosynthesis and the production of secondary metabolites. Salinity-induced decrease in soil osmotic potential and increased concentrations of toxic ions (Na^+ and Cl^-) restrain the uptake of water and essential nutrients by plants. Na^+ and Cl^- concentrations consistently increased in roots, stems and leaves of marjoram (*Origanum majorana* L.) plants in the presence of NaCl (0, 50, 100, and 150 mM). Although root Na^+ decreased, leaf and stem Na^+ was considerably increased with increasing NaCl levels; yet, Cl^- content was invariably increased in all plant parts albeit at a far lower rate than that of Na^+. Salt treatments resulted in decreased K^+ concentration in roots at 100 mM NaCl and in stems at 150 mM NaCl. The K^+ content in leaves was not affected by salt. Ca^{2+} content decreased in roots and stems but was not much affected in leaves. Data suggested a higher allocation of K^+ and Ca^{2+} in leaves than in stems and roots at 100 mM and higher NaCl levels.[15]

In Bishop's weed (*Ammi majus* L.), Na^+ and Cl^- were increased in both shoots and roots while K^+ and Ca^{2+} were decreased with increase in salinity. Plants maintained markedly higher K^+/Na^+ ratio in the shoots than in roots, and the ratio remained >1 even at the highest (160 mM NaCl) salt level.[10] Similar results have been reported in ajwain where Na^+ and Cl^- shoots and roots increased, whereas K^+ and Ca^{2+} consistently decreased with increase in salt level. Plants showed favorable K^+/Na^+ and Ca^{2+}/Na^+ ratios in shoots than in roots with K^+/Na^+ ratio remaining above 1 even at 120 mmol L^{-1} NaCl.[11] Irrigation water salinity above 4 dS m^{-1} significantly enhanced leaf Na^+ content in fennel. The highest and the lowest leaf Mg^{2+} levels were recorded in normal and highest salinity levels (12 dS m^{-1}), respectively. Leaf K^+ and Ca^{2+} contents were not significantly affected by salinity.[99] Increasing salinity (2, 6, and 10 dS m^{-1}) had little influence on plant growth, water relations and the macronutrient levels in celery plants. However, salt stress markedly enhanced the accumulation of Na^+ and Cl^- in the mature leaves but to a much lesser extent in the young leaves.[86]

The data presented here are illustrative: salt effects on mineral nutrition are complex and the results often significantly vary with the crop and experimental conditions. In most of the cases, Na^+ and Cl^- ions tend to increase resulting in the reduced availability of other essential ions such as K^+ and Ca^{2+}. Ion accumulation patterns in different plant parts may be different. Some species often maintain adequate K^+ and Ca^{2+} levels in the foliar and root tissues to counteract adverse effects of Na^+ and Cl^-, especially at low to moderate salt levels. Salinity levels beyond tolerance threshold, however, lead to the breakdown of salt exclusion and avoidance mechanisms resulting in abrupt increases in Na^+ and Cl^- concentrations and a range of salt injury symptoms.

Salinity almost invariably leads to reduced N availability in plants.[36] Similarly, in most of the cases, salt-stressed plants show deficient P levels with adverse consequences for photosynthesis and other energy-dependent growth processes.[83] Elevated Na^+ levels in growing medium usually suppress K^+ supply to plants. K^+ not only acts as an essential cofactor for many enzymes but also plays critical roles in cellular osmotic balance and stomatal regulation.[76] Available evidence suggests that some crop genotypes tend to preferentially accumulate K^+ to partly overcome Na^+ toxicity.[15] In majority of the crop plants, salinity lowers Ca^{2+} levels leading to membrane permeability, EL and other harmful effects.[10] In saline soils, availability of micronutrients such as Fe, Zn, Mn, and Cu may either increase or decrease.[71]

10.3.1.6 ANTIOXIDANT DEFENSE SYSTEM

As previously mentioned, salt stress leads to increased levels of harmful ROS such as superoxide (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH) which, by oxidizing lipids, proteins and nucleic acids, impair the cell structure and functions. To overcome the oxidative damage, plants activate different enzymatic [superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), and peroxidase (PER)] and nonenzymatic antioxidants (e.g., ascorbic acid, α-tocopherol, glutathione, and carotenoids) to scavenge the free radicals.[31] Coriander plants sprayed with 10 μM triacontanol showed higher salt tolerance due to enhanced levels of SOD, CAT, APX, and PER.[59] Inoculation with mycorrhizal strain *Glomus intraradices* improved the concentration and activity of SOD, CAT, PX, APX, and GR enzymes in salt treated (0, 50, 100, and 200 mM NaCl) fenugreek plants and thus reduced oxidative damage compared to nonmycorrhizal plants.[31]

The activity of antioxidant enzymes was significantly increased in response to NaCl stress (150 mM) in Indian mustard (*Brassica juncea* L. Czern.). Exogenous application of salicylic acid (SA) further enhanced the antioxidant enzyme levels.[118] Salinity upregulated CAT levels in fenugreek plants. Seed treatment with ascorbic acid, on the other hand, improved PER and esterase (Est) levels but decreased the CAT activity.[19] The activity of PER and polyphenol oxidase enzymes was increased in response to NaCl-induced salinity (0, 50, 100, 150, and 200 mM) enhancing the tolerance of fenugreek plants against oxidative damage.[88] Certain phenolic compounds also show antioxidant activities and thus prevent the damage caused by ROS, which are inevitably produced when plant metabolism is impaired by environmental stresses. Water deficit enhanced the phenolic content in cumin seeds.[90]

10.3.1.7 OSMOREGULATION

Proline and glycine betaine (GB) are the two major osmoprotectants synthesized by salinized plants to maintain the cellular osmotic balance. Proline is also implicated in removing the ROS, stabilizing the cell organelles and in buffering the cellular redox potential under stress conditions. Salinity stress responsive genes, whose promoters contain proline responsive elements (ACTCAT), are also known to be induced by proline.[23] While soluble and insoluble carbohydrates and proline contents were increased, and other free amino acids were declined with increasing NaCl concentrations (up to 300 mM) in black cumin.[49] NaCl stress (160, 200, 240, and 280 mM) markedly increased the proline and other amino acids in anise and coriander. In contrast, only proline increased but other amino acids decreased in caraway and cumin plants.[123] Shoot proline content significantly increased at 100 mM NaCl level in fennel.[9] Although leaf proline did not increase up to 80 m mol L^{-1}, yet it significantly increased at the highest NaCl level (120 m mol L^{-1}) suggesting a positive role of proline in salt stress adaptation in ajwain.[11] Both proline and GB consistently increased in NaCl treated ajwain plants. Proline and GB levels were about 3.5-fold and 2-fold higher at 150 mM NaCl than control.[117]

Treatment of Gamma ray (0, 25, 50, 100, and 150 Gy) irradiated fenugreek seeds with GB (50 mM) significantly improved the levels of nucleic acids in plants compared to untreated (irradiated) control indicating its protective role against oxidative stress.[73] Mannitol, a compatible solute, increased in NaCl (25, 100, and 300 mM) treated celery plants due to increased activity of mannose-6-phosphate reductase (a key enzyme in mannitol biosynthesis); especially in the young and fully expanded leaves.[32] Soluble sugars increased in the leaves of salinized chili pepper (*Capsicum frutescens* L.) plants. Tolerance of cultivars "Awlad Haffouzz" and "Korba" to the highest NaCl (12 g L^{-1}) level was linked to the corresponding higher concentrations of soluble sugars.[121]

10.3.1.8 HORMONAL CHANGES

Plant hormones, also referred to as phytohormones, comprise of diverse organic compounds which modulate different plant physiological responses. They are produced in one part and are translocated to other parts in trace amounts; they exert a modifying influence on different physiological activities. Chemically synthesized compounds mimicking hormonal action when applied externally are called plant growth regulators (PGRs). Phytohormones may either exhibit a growth promoting (auxins, gibberellins, and cytokinin) or growth inhibiting effect [abscisic acid (ABA) and ethylene].[62] It is seen that the levels of growth promoting phytohormones commonly decline while those of growth inhibitors increase in response to salinity. As a consequence, different growth promoting PGRs are often externally applied to alleviate the salt stress in plants. For example, exogenous application of ABA reduces the ethylene-induced leaf abscission probably by decreasing the accumulation of toxic Cl^- ions in leaves.[55] Several other PGRs have also been successfully used to enhance the salt tolerance in crop plants (see Section 10.4.6) in this chapter.

Salt treatment leads to increase in ABA levels which, in most cases, are positively correlated with leaf and/or soil water potential implying that elevated ABA levels are mainly due to water deficit. It has been shown that only slight increase in ABA concentration enhances the plant adaptation to stresses as higher concentrations may prove inhibitory to plant growth.[120] Salt-stressed ABA to overcome adverse effects of osmotic stress on photosynthesis, growth and plants tend to synthesize translocation of assimilates that also plays a critical role in the expression of salt-induced genes.[112]

ABA accumulation may also favor higher uptake of Ca^{2+} and reduced absorption of Cl^- ions resulting in better CMS and low ethylene-induced leaf abscission, respectively, in salt-stressed plants.[93,120] Although little evidence is available to support the salt stress protective role of ABA in seed spices, yet some experimental findings have established the plant growth promoting effects of ABA application in crops such as coriander possibly due to tangible improvements in stress tolerance.[94] In most of the cases, accumulated ABA rapidly disappears subsequent to stress release to allow the normal plant metabolism.[120]

10.3.2 EFFECTS ON PLANT GROWTH

Salinity adversely affects plant growth and yield by decreasing the seed germination, plant stand, biomass production, flowering, and seed formation in seed spices. Considerable variation is noted with respect to genotypes, crop growth stages as well as the level and duration of the salt treatment.

10.3.2.1 SEED GERMINATION AND SEEDLING ESTABLISHMENT

In most crop plants, seed germination, seedling emergence, and plant survival are particularly sensitive to salinity stress. High levels of salt may either partially or completely inhibit the seed germination. Salt stress lowers the seed germination primarily by decreasing the osmotic potential of the soil solution which in turn retards the water absorption by seeds. Excessive accumulation of Na^+ and Cl^- ions proves toxic to the seed embryo. In four umbelliferous seed spices exposed to different salt levels, 50% reduction in seed germination (G_{50}) was seen at 120 mM NaCl in anise, at 150 mM NaCl in coriander, and at 200 mM NaCl in caraway and cumin each.[122] Seedling dry weight of anise and coriander was decreased with increasing salinity, but seedling growth of caraway and cumin appeared to be stimulated by NaCl concentrations up to 80 mM.[123] Increasing salinity reduced the seed germination and vegetative growth in coriander and fennel crops. Germination and plant height were not affected up to 5.0 dS m^{-1} salinity. Fennel showed higher salt tolerance than coriander under high salinity levels.[67] Salinity significantly decreased percent seed germination, rate of germination and the root and shoot lengths in fenugreek seedlings. Root length was more affected than shoot length.[57]

Although seed germination was not significantly affected up to 200 mM NaCl, yet further increase to 300 mM NaCl decreased germination by about 70% compared to control.[8] Different accessions of fenugreek exposed to varying NaCl levels (0, 4, 6, 8, 10 dS m^{-1}) germinated and grew at low salinity, but germination was delayed as NaCl concentration increased and germination was almost completely inhibited at 10 dS m^{-1} NaCl.[7] Salinity significantly reduced germination percentage and the growth of shoots and roots in ajwain. Seed treatment with 0.2% chitosan solution, however, improved the salt tolerance in ajwain as evident from increased shoot and root lengths, shoot dry weight, and RWC in salinized plants (4–12 dS m^{-1}).[66] Salt stress severely reduced seed germination in ajwain with virtually no germination observed at very high salinity (18 dS m^{-1}).[74]

Seed germination and seedling emergence rate, seedling length and weight and radical length were unaffected up to 9 dS m^{-1} salinity in nigella. While seed germination rate was very high (94.8%) in normal soils, it was reduced to about 90% at 15 dS m^{-1} and consistently decreased with increasing salinity. No seed germination was seen at a salinity level of 36 dS m^{-1}.[34]

10.3.2.2 VEGETATIVE GROWTH AND BIOMASS PRODUCTION

As with other crops, salt stress invariably causes significant yield reduction unless appropriate interventions are applied to overcome the salt hazard. Under field conditions, salt-stressed crops show stunted and sparse growth resulting in lower productivity (Fig. 10.1).

FIGURE 10.1 (See color insert.) Sparse and stunted plant growth in fenugreek in a saline water irrigated field at Hisar, Haryana, India (Courtesy: Rameshwar Lal Meena).

Saline irrigated (0, 60, 120, and 180 mM NaCl) fenugreek plants showed decline in plant dry matter and chlorophyll production with the highest reductions observed at 180 mM NaCl level than control. Application of silicon (0.2 mM Na_2SiO_3) partially mitigated the salt injury.[78] Increasing salinity in irrigation water (0.25, 1, 2, 4, 6, 8, 10, and 12 dS m^{-1}) resulted in decreased water consumption, plant height, plant fresh and dry weights, and seed yield in fennel. Based on these observations, threshold salt tolerance for fennel was found to be 2.64 dS m^{-1} (salinity at which yield starts to decrease) with slope of 4.5% (yield decline with per unit increase in electrical conductivity) pointing to the moderately salt sensitive nature of fennel.[99]

NaCl (1500 ppm) treated thyme (*Thymus vulgaris* L.) showed significant decrease in plant height, number of branches and fresh and dry plant mass.[27] NaCl-induced salinity (0, 3, and 6 dS m^{-1}) hampered shoot length and fresh and dry shoot weight in nigella but root length increased with increasing salinity. In control plants, the mean shoot length was 12.58 cm, while at 3 and 6 dS m^{-1} salinity levels, it reduced to 8.4 and 6.05 cm, respectively.[52] Salinized (12 dS m^{-1}) fennel plants showed considerable decrease in plant height, leaf weight, and bulb weight which declined by 33%, 49%, and 71%, respectively, compared to control.[24]

Increasing salt concentrations (0, 2, 4, 6, 8, and 10 dS m^{-1}) significantly decreased the seedling height, shoot and root lengths, seed germination percentage, germination rate, fresh, and dry seedling weight and seed vigor index in fennel and cumin.[50] Pot experiments on tolerance of seed spices revealed that decrease in the seed and biomass yield of coriander decreased 6 and 28% and 3 and 23%, respectively. Similar results have been obtained in case of fennel although it emerges that under similar conditions fennel is relatively more tolerant to saline water irrigation then coriander.[115] The experiments also established benefits of conjunctive use as a management option to use highly saline waters.

Similar results for the fennel crop were later reported by Meena et al.[69] additionally revealing the benefits of organic manures in mitigating the adverse effects of saline irrigation. In sodic soils, emergence of secondary branches and seed setting are considerably depressed in coriander resulting in low seed yield than yield obtained in normal soils. The cation composition of stover revealed Na^+ inclusion mechanism with narrow K^+/Na^+ and Ca^{2+}/Na^+ ratios. The study further revealed that the fennel crop could tolerate medium level of sodicity.[40]

10.3.2.3 SEED YIELD

Increasing NaCl concentrations (0, 40, 80, 120, and 160 mM) caused significant reductions in the fresh and dry weights of shoots and roots as well as seed yield in Bishop's weed.[10] Although NaCl stress (0, 40, 80, and 120 mmol L^{-1}) significantly reduced both plant dry mass and seed yield in ajwain, yet the seed yield was relatively more adversely affected. While shoot dry biomass decreased by about 27%, reduction in seed yield was almost 50% than control at 120 mmol L^{-1} NaCl.[11] Salt stress (0, 40, and 80 mM NaCl) significantly decreased the fresh and dry plant weight, umbels per plant, 1000 seed weight and seed yield in fennel. Addition of sodium silicate (0.5 and 1 mM) into saline solution mitigated these adverse effects.[89] Salinized plants (75 mM NaCl) of coriander showed about 36% decrease in seed yield than control.[80] With increase in salinity from 0.3 to 9 dS m^{-1}, the mean biological and seed yields decreased from 550.2 to 268.6 g m^{-2} and 105.5 to 40.2 g m^{-2}, respectively, in black cumin.[34]

Experiments conducted on dill on saline black soils of different unirrigated sites in Khanpur, Warsada, and Bamangam villages of Anand district showed that the *in-situ* salinity was negatively correlated with seed yield of dill. The study revealed that the dill can profitably be grown on saline black soils (up to 4–6 dS m^{-1} salinity) without any irrigation during winter season.[48] With a unit increase in salinity beyond this, the yield reduction was 0.043 t ha^{-1}. It is also revealed that the water of submarginal quality (salinity ~4 dS m^{-1}) can be used without any significant yield reduction.[48] Chauhan[21] revealed that while seed and stover yields of fennel decreased with increasing salinity of irrigation water, 1000 seed weight was not significantly affected even up to 8 dS m^{-1} salinity (Table 10.3). Salinity–induced reduction in plant growth and seed yield in cumin crop are given in Figure 10.2. Table 10.4 indicates effects of salinity levels on yield attributing characteristics and yield of fennel crop.

TABLE 10.3 Reduction in Seed and Total Biomass Yield (%) of Coriander and Fennel Under Different Modes of Saline Water Irrigation.

Irrigation water salinity (dS m^{-1})	Coriander (t ha^{-1})		Fennel (t ha^{-1})	
	Biomass	Seed yield	Biomass	Seed yield
3.7	–	–	–	–
3.7 and 8.7[a]	3	6	2	5
8.7	23	28	15	21

"–": Assumed no reduction in yield.

[a]Alternate irrigation beginning with 3.7 dS m^{-1}.

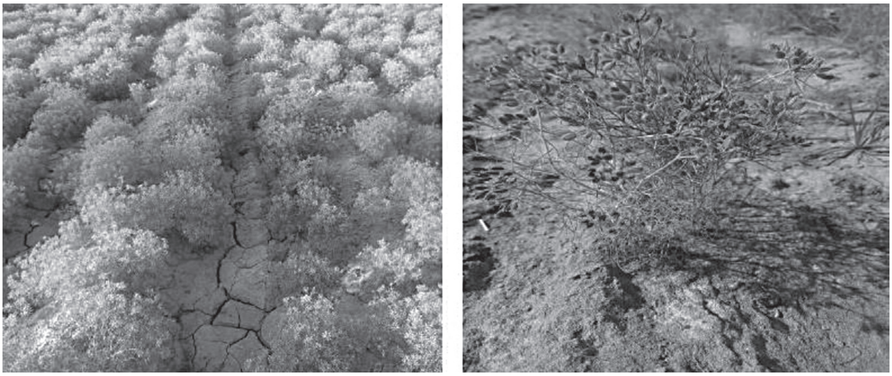

FIGURE 10.2 (See color insert.) Adverse effects of salinity on vegetative growth (left) and seed formation (right) in cumin crop (Jaisalmer, Rajasthan, India).

TABLE 10.4 Effect of Salinity Levels on Yield Attributing Characteristics and Yield of Fennel Crop.

Salinity of irrigation water	Weight of 1000 seeds			Seed yield			Stover yield		
	2010–2011	2011–2012	Mean	2010–2011	2011–2012	Mean	2010–2011	2011–2012	Mean
dS m^{-1}		g				t ha^{-1}			
BAW	6.06	6.04	6.05	1.17	1.11	1.14	5.52	5.35	5.44
4	6.01	6.00	6.00	1.09	1.05	1.07	5.43	5.30	5.37
6	6.01	6.00	6.00	1.03	1.01	1.02	5.42	5.28	5.35
8	5.92	5.90	5.91	0.92	0.89	0.91	4.67	4.61	4.64
CD at 5%	NS	NS	–	0.117	0.2.10	–	0.89	0.87	–

BAW, best available water.

10.3.2.4 SEED OIL YIELD AND QUALITY

Although increasing salinity (0–120 mmol L^{-1} NaCl) adversely affected the seed yield in ajwain, yet seed oil concentration was not affected.[11] Seed oil yield in fennel consistently decreased with the increasing salinity (0–100 mM NaCl).[9] Seed essential oil production decreased with increasing NaCl levels (0–160 mM) in Bishop's weed.[10] Despite a significant reduction in seed yield, salinized coriander plants showed increase in essential oil yield with increasing NaCl levels. Essential oil yield increased by 77% and 84% at 50 and 75 mM NaCl, respectively, than control. Again, the major constituents of oil (linalool and camphor) also increased with increasing salinity.[80]

Dill plants grown under saline conditions (0, 4, 8, and 12 dS m^{-1}) showed significant reductions in leaf dry weight per plant. Yet, flower and seed dry weights did not significantly decrease and essential oil yield even increased with increasing salinity.[44] NaCl stress (60 mM) decreased the seed yield of nigella by about 58% than control. Essential oil yield increased by 0.53, 0.56, and 0.72% at 20, 40, and 60 mM NaCl level, respectively, over control. Salinity enhanced the linoleic acid percentage but did not affect the unsaturated degree of the fatty acids pool and thus oil quality.[20] In spite of almost 50% decrease in seed yield, salinity did not significantly decrease the seed oil percentage in black cumin.[34] Moderate sodicity levels (ESP—20 and 30) slightly suppressed the seed yield in coriander and fennel but seed oil yield was not affected in both the crops.[104] These data tend to show that salt-stress-induced reductions in seed yield are compensated, to a great extent, by increased essential oil levels in different crops.

10.4 SALINITY MANAGEMENT OPTIONS

A range of solutions have been proposed to enhance the salt tolerance in crop plants or, alternatively, by modifying the growing conditions to get higher yields. In seed spices, enhanced adaptation to salt stress can be achieved by developing the high yielding and salt tolerant genotypes, presowing seed treatments, exogenous applications of chemicals and PGRs, supplemental nutrition and the use of microbial inoculants. Use of salt tolerant cultivars (STCs) is an economically viable and environment-friendly approach to obtain stable yields in saline soils. Cultivation of plants having inherent ability to endure the high salt levels implies reduced dependence on chemical soil ameliorants to make the root zone conditions favorable to plant growth and yield. Such measures are briefly discussed in the succeeding sections.

10.4.1 GENETIC IMPROVEMENT FOR SALT TOLERANCE

Conventional breeding methods as well as advanced biotechnological techniques have been used with varying degree of successes to develop STCs in crop plants. Although traditional breeding approaches have led to the identification of a few STCs in different crops, yet the rate of success through conventional improvement is rather slow due to polygenic inheritance of the salt tolerance. Owing to their cross pollinated nature (except fenugreek), seed spices exhibit high degree of heterozygosity and polymorphism for different traits. Nonetheless, low genetic variability has been reported for salinity tolerance in most of such species. To overcome this problem, mass screening of seed spice crops is often the method of choice to identify salt tolerant lines for commercial cultivation as well as for use as parents in breeding programs. Over the years, such screening programs have led to the identification of a handful of STCs in different seed spice crops (Table 10.5).

TABLE 10.5 Genotypic Differences in Seed Spices Under Salt Stress.

Crop	Finding	References
Cumin	Genotype RZ-19 showed higher salt tolerance than UC-198 and RZ-209. Adverse effects of salinity (10 dS m^{-1}) on total chlorophyll, K^+/Na^+ ratio, soluble protein, free amino acids, starch, reducing sugars, and nitrate reductase activity were considerably less in RZ-19 than sensitive genotypes	[39]
Coriander	On the basis of seed germination and seedling growth under NaCl stress (25, 50, 75, and 100 mM), cultivars PD-21 and Kalmi were found to be highly and moderately salt tolerant, respectively while Pant Haritma was categorized as salt sensitive	[60]
Fenugreek	Among the eight cultivars exposed to varying NaCl levels (0, 4, 6, 8, and 10 g L^{-1}), Berber was found to be the most salt tolerant and Damar I as the most salt sensitive	[38]
	Only two accessions (F-3 and F-98) showed about 40% germination stress index, while it was low/very low (5–34%) in other six accessions at 10 dS m^{-1} salinity	[7]
Fennel	Among the four cultivars (HF-107, Local BRS, NDF-7, NDF-9) grown in moderately sodic soils (ESP ~ 30), HF-107 and NDF-7 produced the highest (1956 kg ha^{-1}) and the lowest (1078 kg ha^{-1}) seed yields	[40]
Sweet fennel	Cultivars Dulce, ZefaFino, and Selma differentially responded to saline irrigation. ZefaFino recorded the highest plant length, leaf number, plant fresh weight, leaf yield, and essential oil content compared to other cultivars	[119]
Chili pepper	Higher proline accumulation in leaves was linked to high salt tolerance (NaCl 12 g L^{-1}) of cultivars Awlad Haffouzz and Korba in comparison to cultivar Souk jedid	[121]

Induced mutagenesis may also be tried to create genetic variability for identifying the salt tolerant mutants. Dimethyl sulfate (DMS; 0, 1000, and 2000 ppm) treatment of fennel seeds exposed to saline irrigation (0, 50, 100 mM NaCl) resulted in two salt tolerant mutants in the second generation. While mutant 1 was obtained from the 1000 ppm DMS treatment, mutant 2 was isolated from 2000 ppm DMS treated seeds grown under 100 mM

NaCl. Both the mutants were superior to the wild type (control plants) with respect to plant height, branching, leaf production, stem diameter, total seeds weight, oil percentage, and seed oil yield.[43]

Advances in molecular marker technology in the recent past have made it possible to dissect the quantitative trait loci (QTLs) linked to salt tolerance. QTLs represent those genomic regions in the plants where the major genes controlling salt tolerance are located. Mapping of such genomic stretches helps improve the selection efficiency by differentiating the candidate genes from the other genes. QTL mapping may also be helpful in identifying the candidate genes responsible for modulating plant salt tolerance during different growth stages such as seed germination, vegetative growth, and seed setting.[37]

Genetic transformation technology has also made rapid strides in the recent times and has significantly contributed to crop improvement for desirable traits. The *SbNHX1* gene, cloned from halophyte *Salicornia brachiata* was introgressed in cumin using *Agrobacterium*-mediated transformation method. *SbNHX1* gene encodes a vacuolar Na^+/H^+ antiporter and is involved in the compartmentalization of excess Na^+ ions into the vacuole and maintenance of ion homeostasis. Transgenic lines (L3, L5, L10, and L13), overexpressing the *SbNHX1* gene, showed higher photosynthetic pigments (chlorophyll *a*, *b*, and carotenoids) and lower electrolytic leakage, lipid peroxidation, and proline contents compared to wild type plants under salinity stress.[85]

10.4.2 SELECTION OF SALT TOLERANT CROPS AND CULTIVARS

Similar to other economically important plants, seed spice crops vary with each other in their relative salt tolerance. Some of the findings presented in Table 10.6 point to the distinct salt tolerance threshold levels ranging from salt sensitive to highly salt tolerant in different species.

Different seed spice crops employ varied mechanisms to overcome the salt injury. High salinity tolerance in celery is attributed to the higher accumulation of mannitol which acts as an efficient osmo-protectant[32] and the partitioning of toxic Na^+ and Cl^- ions into older leaves so that young and actively photosynthesizing leaves are protected from the salt ions.[86] Although a few studies have indicated moderate salt sensitivity in fennel,[2,99] Graifenberg et al.[45] found markedly lower salt tolerance threshold ($EC_e \sim 1.5$ dS m^{-1}) in the tested cultivars (Monte Bianco and Everest) which lacked the ion partitioning mechanism to prevent Na^+ and Cl^- accumulation in the young leaves.[45] It implies that salt stress adaptation traits may vary across genotypes in a particular species.

Elevated proline levels and the maintenance of high shoot K^+ /Na^+ ratios contribute to the high salt tolerance in nigella[49] and ajwain,[10] respectively.

TABLE 10.6 Relative Salt Tolerance in Seed Spices.

Crop	Salt tolerance	References
Ajwain	Moderately salt tolerant; salt stress adaptation is linked to the maintenance of high K^+/Na^+ and Ca^{2+}/Na^+ ratios in shoots and roots	[11]
Bishop's weed	Moderately salt tolerant; salt tolerance is achieved by the maintenance of high shoot K^+/Na^+ ratio and proline accumulation in shoots	[10]
Celery	Salt tolerant species; mannitol accumulation and partitioning of Na^+ and Cl^- ions in the older leaves contribute to salt tolerance	[32,86]
Dill	Highly salt tolerant; NaCl-induced salinity up to 12 dS m^{-1} does not affect seed and oil yield	[44]
Fennel	Moderately salt sensitive; threshold salinity at which yield starts to decline is around 2.5 dS m^{-1}	[99]

10.4.3 SEED PRIMING

Different types of seed priming methods (e.g., hydro-priming, osmo-priming, and priming with chemicals and PGRs) have proved effective in overcoming the salt-induced decrease in seed germination and seedling establishment in seed spices. Coriander seeds primed with aerated solutions of 0.13 M NaCl and $CaCl_2$ showed improved salt tolerance as evident by higher seed germination, seedling emergence, better growth and improved levels of K^+ and Ca^{2+} than unprimed seeds.[14] The beneficial effects of hydration–dehydration seed treatment on germination of many seed spice crops have been demonstrated.[95] Seed priming with distilled water (hydro-priming) and Zn_2SO_4 shortened the mean germination time in cumin under NaCl stress. However, hydro-primed seeds recorded significantly higher final germination rate as well as better seedling growth suggesting toxicity caused by Zn_2SO_4 to the seed embryo.[79]

Hydro-priming for 6 h followed by matrix priming with synthetic soil for 72 h hastened the seed germination in cumin; over 90% of the primed seeds germinated on 4th day after inoculation compared to delayed germination (on 8th day) in untreated seeds. Genotype "GC-4" was found to be more responsive to priming than "RZ-209".[95] Different methods of seed priming [SA, gibberellic acid (GA), and hydro-priming] improved the length and dry weights of plumule and radicle in NaCl stressed (50 and 100 mM) fenugreek. However, both SA and GA treatments gave better results as evident from increased chlorophyll and proline levels and decrease in MDA content than salinized (both unprimed and hydro-primed) seedlings.[33] SA (0.00001 mM) primed ajwain seeds showed improved germination percentage and rate, radicle and plumule lengths and seed vigor up to 12 dS m^{-1} salinity level.[74] Seed priming with SA (0.2 mM) and KNO_3 (3%) improved different germination traits under osmotic stress in black cumin.[17]

10.4.4 NUTRIENT MANAGEMENT

Organic manure application enhanced the salt tolerance of fennel cultivar "Dulce." Vegetative growth parameters such as plant height, leaf number, plant fresh and dry weights, leaf yield, macronutrient levels (N, P, and K), K^+/Na^+ ratio and proline contents increased by organic manuring.[2] Application of magnetite iron and sheep manure improved the plant height, branching, plant fresh and dry weights, umbels per plant, fruit yield per plant, essential oil percentage in fruits, and essential oil yield per plant in saline irrigated fennel.[70] Increased levels of nitrogen and phosphorus fertilizers enhanced the seed and stover yields in nigella under sodic conditions.[41] Application of 90 kg ha^{-1} N and 50 kg ha^{-1} P resulted in 37% higher seed yield in coriander while 80 kg ha^{-1} N and 25 kg ha^{-1} P resulted in significantly higher (67%) seed yield in fennel over unfertilized control plants in moderately sodic soils (ESP ~ 20 and 30).[42] Plant growth enhancement due to application of organic inputs in fennel crop is shown in Figure 10.3.

FIGURE 10.3 Organic manures improved plant growth in saline irrigated (~3 dS m^{-1}, right) fennel compared to control (saline irrigated but untreated, left) under arid conditions of Hisar, Haryana, India.

10.4.5 MICROBIAL INOCULANTS

It has been shown that arbuscular mycorrhizal fungi (AMFs) improve the plant growth under stress conditions by increasing the nutrient availability, maintaining a favorable K^+/Na^+ ratio and osmotic adjustment by accumulation of compatible solutes such as proline or soluble sugars. AMF-treated plants exhibit higher photosynthesis and water use efficiency under salt stress compared to stressed but nonmycorrhizal plants.[6]

Inoculation with AMF *Glomus intraradices* significantly decreased the extent of salt-induced (0, 50, 100, and 200 mM NaCl) ultrastructural alterations such as protoplasm shrinkage, grana disorganization, thylakoid swelling, chloroplast membrane disintegration, and aggregation of chromatin in nucleus in fenugreek.[103] Lesser damage in AMF-inoculated plants may be attributed to higher osmolyte (GB and sugars) and polyamines concentrations, and more and bigger plastoglobules.[30] *Glomus mosseae* inoculation enhanced shoot and root dry weights, leaf area, photosynthetic pigments, and soluble sugars in NaCl-stressed (0, 25, 50, and 100 mM) chili (cv. Zhongjiao 105) plants.[65] Plant growth-promoting rhizobacteria (PGPR) is a group of bacteria present in the rhizosphere. PGPR protect the plants against various biotic and abiotic stresses. They alleviate salt stress in plants by enhancing the biosynthesis of phytohormones and enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which suppresses the endogenous levels of ACC—a precursor of ethylene. Decrease in ACC availability hampers ethylene production and thus lessens the extent of ethylene-induced leaf abscission and other harmful effects.[26]

Seed treatment with biofertilizers containing different bacterial and fungal isolates improved the salt tolerance in coriander. Nitroxin (including *Azospirillium* and *Azotobacter*) and Super nitroplus (including *Aspirillium*, *Bacillus subtilis*, *Pseudomonas fluorescens*) applications resulted in better plant growth and higher levels of chlorophyll pigments (*a*, *b*, and *a*+*b*); especially up to 60 mM NaCl stress.[91] Seed inoculation with *Rhizobium meliloti* strain “FRS-7” gave the best results with regard to shoot length, shoot dry weight, shoot total nitrogen, root length, root dry weight, root total nitrogen, seed yield, 1000 grain weight, number of root nodules, and nodule fresh and dry weights in fenugreek crop grown under semiarid conditions. The performance of this strain was even better than 20 kg N ha^{-1}. Seed yields obtained with FRS-7 during two consecutive years were about 36.8% and 45.9% higher over control.[102]

PGPR (*Paenibacillus polymyxa* and *Azospirillum lipoferum*) treatment reduced salt stress and resulted in significant improvements in plant height, number of branches, plant fresh and dry weights, essential oil percentage, and essential oil yield in sweet basil.[1] Use of PGPR (*Azospirillum lipoferum* and/or *Bacillus megaterium*) significantly improved the plant growth, photosynthetic pigments and yield in saline irrigated (~3 and 6 dS m^{-1}) ajwain plants.[63]

10.4.6 PLANT GROWTH REGULATORS AND BIOSTIMULANTS

As the levels of plant-growth-promoting phytohormones decline in salt-stressed plants, several studies have been conducted to assess the effect of synthetic PGRs to overcome the salt injury in different crops. SA, a plant bioregulator, has been extensively used to alleviate drought and salt stresses in crop plants. Application of gibberellic acid (GA_3) has been found to counteract some of the adverse effects of salinity in plants.[110] Jasmonates can also play an important role in plant salt tolerance. Polyamines, known to elicit diverse physiological activities in plants such as cell division, tuber formation, root initiation, flower development, and fruit ripening, are also implicated in improving abiotic stress tolerance.[51] Brassinosteroids have received attention due to their beneficial influence in improving the salt tolerance.[5] Foliar application of indole acetic acid and kinetin alleviated the adverse effects of salinity such as decrease in plant biomass production, chlorophyll content, and RWC in maize plants exposed to 100 mM NaCl.[61]

Application of SA improved antioxidant enzyme levels, leaf water potential, RWC, leaf pigments and osmolytes, and seed essential oil content in fennel genotypes exposed to drought stress.[12] SA (5 and 10 μM) treatment also increased the drought tolerance of nigella seedlings as evident from negligible injury symptoms in the pretreated plants.[56] Fenugreek cultivars “Deli Kabul” and “Kasuri” showed significant reductions in plant biomass in saline (100 mM NaCl) than normal soils. However, biomass production was less reduced in “Deli Kabul” as evident from higher shoot fresh weight compared to “Kasuri.” Foliar spray of SA (100 ppm) overcame salt-induced growth reduction in both the cultivars.[16]

Coriander plants sprayed with 10 μM triacontanol showed higher salt tolerance due to enhanced levels of antioxidant enzymes (SOD, CAT, APX, and PER).[59] Application of a nonionic surfactant (3 ppm) enhanced the photosynthetic activity in fenugreek plants at moderate and high salinities

(6–10 dS m^{-1}).[25] Soil drenching with humic acid (3 g L^{-1}) and foliar spray of dry yeast (20 and 25 g L^{-1}) effectively alleviated salt stress in fennel by increasing K^+ accumulation and lowering Na^+ uptake by the plants.[72]

10.5 CONCLUSION

Critical review of the adverse effects of soil/water salinity on germination and seedling establishment, vegetative growth and biomass production, seed yield and seed oil yield, and quality of seed spice crops reveal that not only crops but varieties within the crops respond differently to salt stress. Apparently, selection of salt tolerant crops and cultivars is suggested as one of the major intervention to improve production and productivity of seed spices cultivated in saline environments. A case is build-up to suggest genetic improvement of these crops. Until then, some nonstructural interventions such as seed priming, nutrient management, use of microbial inoculants, and application of PGRs and biostimulants can be pursued to blunt the adverse effects of salts on crop productivity.

10.6 SUMMARY

The introductory part of this chapter highlights the role of seed spices in human diets and healthcare followed by a brief account of the recent trends in production and export of seed spices with special reference to India. Introduction section also briefly deals with expanding salinity problem and the need to overcome the salt stress for higher crop productivity. While discussing the plant responses to salt stress, various adverse effects of salinity on plant physiological relations with special reference to seed spices have been dealt with.

Continuing with plant response to salinity, adverse effects on seed germination and seedling establishment, vegetative growth and biomass production, seed yield and seed oil yield and quality of seed spice crops are critically analyzed. Toward the end of this chapter, conventional approaches and the advanced techniques of salinity management in seed spices are thoroughly discussed. Some of the options discussed include selection of salt tolerant crops and cultivars, seed priming, nutrient management, microbial inoculants and application of PGRs and biostimulants. Genetic improvement for salt tolerance is included as it may be prove to be the most eco-friendly approach to manage saline environments in the future.

KEYWORDS

- **abiotic stresses**
- **osmoregulation**
- **physiological mechanisms**
- **salinization**
- **seed spices**
- **stomatal activity**
- **water potential**

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