Chapter 10
Actions of Biological Trace Elements in Plant Abiotic Stress Tolerance

Mirza Hasanuzzaman, Kamrun Nahar, Anisur Rahman,
Jubayer Al Mahmud, Md. Shahadat Hossain, Md. Khairul Alam,
Hirosuke Oku, and Masayuki Fujita

Abstract With the increase of global population, the demand for food crops, oil, fiber and other by-product yielding crops is increasing. In contrast to this increasing demand, abiotic stresses hinder the productivity of plants. Abiotic stresses sometimes reduce more than half of the crop yields. To attain global food security, understanding of plant responses to abiotic stresses is crucial because this is the prerequisite for developing approaches/tools for improving plant stress tolerance. Trace elements are nutrients required in small quantities to facilitate a range of physiological functions. These elements stimulate growth but are not essential. Some are essential only for certain plant species or required under a given condition. Trace elements not only improve plant physiological processes and growth but play roles in improving plant stress tolerance. However, the actual physiological functions of trace elements in conferring abiotic stress tolerance are still under study. This chapter focuses

---

M. Hasanuzzaman (✉)
Molecular Biotechnology Group, Center of Molecular Biosciences, Tropical Biosphere Research Center, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan

Department of Agronomy, Faculty of Agriculture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh
e-mail: mhzsauag@yahoo.com

K. Nahar
Department of Agricultural Botany, Faculty of Agriculture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh

Laboratory of Plant Stress Responses, Faculty of Agriculture, Kagawa University, Miki-cho, Kita-gun, Kagawa 761-0795, Japan

A. Rahman
Department of Agronomy, Faculty of Agriculture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh

Laboratory of Plant Stress Responses, Faculty of Agriculture, Kagawa University, Miki-cho, Kita-gun, Kagawa 761-0795, Japan

M. Naeem et al. (eds.), *Essential Plant Nutrients*,
DOI 10.1007/978-3-319-58841-4_10

on the roles of trace elements emphasizing especially the recent advances on the actions of biological trace elements in plant abiotic stress tolerance.

Keywords Abiotic stress • Trace elements • Antioxidants • Phytoprotectants • Metabolites

10.1 Introduction

With the increase of global population, the demand of food crops, oil, fiber, and other by-product yielding crops is increasing (Condon et al. 2004; Morison et al. 2008). In contrast to this increasing demand, abiotic stresses hinder the productivity of plants. Abiotic stresses sometimes reduce more than half of the crop yields (Wang et al. 2003). Climate prediction models demonstrate the frequency of occurrence of different abiotic stresses including salinity, drought, flooding, extreme temperature, UV radiation, ozone, and metal toxicity that have increased to a great extent, compared to the previous decades (IPCC 2008; Mittler and Blumwald 2010). Under stressful conditions, plants are subjected to various physiological and metabolic changes throughout their life cycles starting from germination to final harvest. These changes include inhibition of germination, decreased growth, less photosynthesis, lower dry matter assimilation, water imbalance, impaired nutrient uptake, and ultimate reduction of yield and quality (Hasanuzzaman et al. 2012a, b, 2013a, b, c, d, 2014a, b, 2015, 2016). To attain global food security, understanding of plant responses to abiotic stresses is crucial because this is the prerequisite for developing approaches/tools for improving plant stress tolerance (Condon et al. 2004; Morison et al. 2008). In response to abiotic stresses, antioxidants, hormones, osmoprotectants, and many other essential metabolites are altered which have major roles to defend abiotic stresses. Traditional crop improvement methods are time-consuming, costly, sometimes uncertain, or unsuccessful and sometimes cause crop loss due to

---

J.A. Mahmud
Laboratory of Plant Stress Responses, Faculty of Agriculture, Kagawa University,
Miki-cho, Kita-gun, Kagawa 761-0795, Japan

Department of Agroforestry and Environmental Science, Faculty of Agriculture, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh

M.S. Hossain • M. Fujita
Laboratory of Plant Stress Responses, Faculty of Agriculture, Kagawa University,
Miki-cho, Kita-gun, Kagawa 761-0795, Japan

M.K. Alam
School of Veterinary and Life Sciences, Murdoch University, Perth, WA, Australia

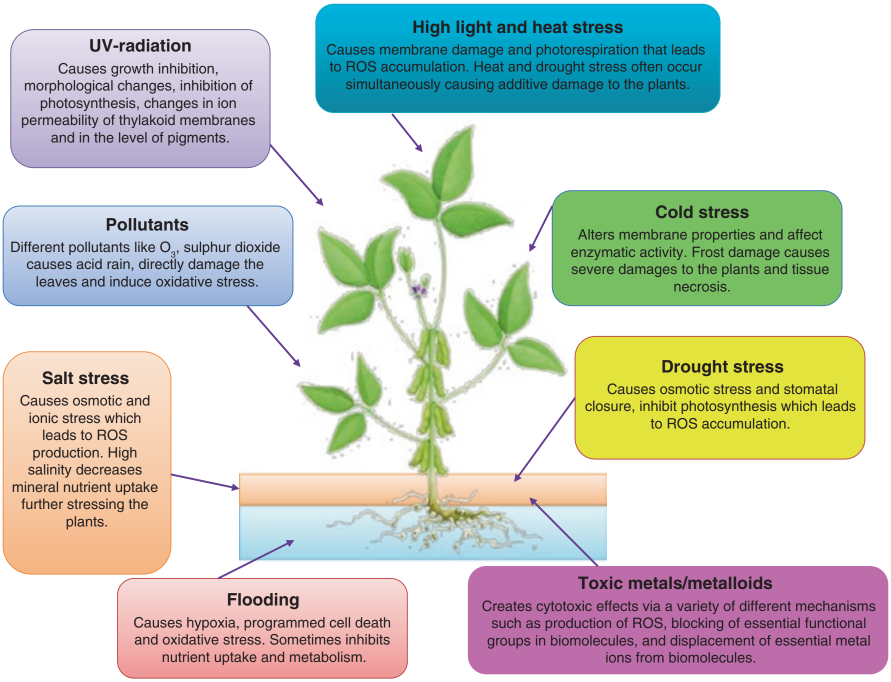
H. Oku
Molecular Biotechnology Group, Center of Molecular Biosciences, Tropical Biosphere
Research Center, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan

evolution or genetic degradation. The use of exogenous phytoprotectants including micronutrient or trace elements is potent approaches to improve plant abiotic stress tolerance (Hasanuzzaman et al. 2011a, b, 2013a, b, c; Nahar et al. 2015a).

Trace elements are nutrients required in small quantities to facilitate a range of physiological functions. These elements stimulate growth but are not essential. Some are essential only for certain plant species or required under a given condition. The micronutrients or trace elements may include iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo), chromium (Cr), cobalt (Co), nickel (Ni), selenium (Se), silicon (Si), etc. Trace elements not only improve plant physiological processes and growth but play roles in improving plant stress tolerance. For instance, Si has been proved to improve plants' tolerance against drought, salinity, high temperature, chilling, UV radiation, nutrient imbalance, and metal toxicity (Raven 2001; Liang et al. 2007; Ma and Yamaji 2008; Hasanuzzaman and Fujita 2011; Ahmed et al. 2012). Plant species supplemented with Se have shown enhanced resistance to salinity (Hawrylak-Nowak 2009; Hasanuzzaman et al. 2011a, b), drought (Hasanuzzaman et al. 2010; Hasanuzzaman and Fujita 2011), extreme temperature (Djanaguiraman et al. 2010; Hawrylak-Nowak et al. 2010), metal toxicity (Hasanuzzaman et al. 2012b), and UV radiation (Yao et al. 2010). Selenium enhances reactive oxygen species (ROS) and oxidative stress tolerance (Hasanuzzaman et al. 2010; Hasanuzzaman and Fujita 2011). Exogenous Zn improved cadmium (Cd) tolerance and increased biomass accumulation by reducing its uptake and Cd-induced membrane damage (Wu and Zhang 2002). Zinc application reduced sodium uptake, enhanced antioxidants, and reduced salt-induced lipid peroxidation and electrolyte leakage (Aktas et al. 2006; Tavallali et al. 2010). Zinc also increased seed yield and thousand kernels weight against drought stress (Monjezi et al. 2012). Exogenous application of boron (B) conferred drought tolerance (Moeinian et al. 2011; Abdel-Motagally and El-Zohri 2016), salt tolerance (Salim 2014), and aluminum (Al) tolerance (Zhou et al. 2015). Salt (Pandya et al. 2004), Cd (Pal'ove-Balang et al. 2006; Peng et al. 2008; Sebastian and Prasad 2015), and drought (Upadhyaya et al. 2012) stresses were alleviated by exogenous manganese (Mn) application. However, the actual physiological functions of trace elements in conferring abiotic stress tolerance are still under study. Considering their importance, this chapter focuses on the roles of trace elements emphasizing specially the recent advances on the actions of biological trace elements in plant abiotic stress tolerance.

10.2 Abiotic Stress: The Worst Enemy for Plants

Unlike animals, plants are sessile organisms and thus are bound to grow in the same habitat fighting with various environmental factors termed as abiotic stress. In the era of climate change, plants are constantly suffering from various abiotic stresses like salinity, drought, extreme temperature, flooding, metal toxicity, air pollution, ozone, UV radiation, and so on. These episodes are becoming more common due to rapid changes in climate. These stressors, alone or in



UV-radiation
Causes growth inhibition, morphological changes, inhibition of photosynthesis, changes in ion permeability of thylakoid membranes and in the level of pigments.

High light and heat stress
Causes membrane damage and photorespiration that leads to ROS accumulation. Heat and drought stress often occur simultaneously causing additive damage to the plants.

Pollutants
Different pollutants like O_3, sulphur dioxide causes acid rain, directly damage the leaves and induce oxidative stress.

Cold stress
Alters membrane properties and affect enzymatic activity. Frost damage causes severe damages to the plants and tissue necrosis.

Salt stress
Causes osmotic and ionic stress which leads to ROS production. High salinity decreases mineral nutrient uptake further stressing the plants.

Drought stress
Causes osmotic stress and stomatal closure, inhibit photosynthesis which leads to ROS accumulation.

Flooding
Causes hypoxia, programmed cell death and oxidative stress. Sometimes inhibits nutrient uptake and metabolism.

Toxic metals/metalloids
Creates cytotoxic effects via a variety of different mechanisms such as production of ROS, blocking of essential functional groups in biomolecules, and displacement of essential metal ions from biomolecules.

Fig. 10.1 Major abiotic stresses for plants and their general effects (Hasanuzzaman et al. 2016; With Permission from Elsevier)

combination, attack plants, and thus the consequence is often unpredictable and becomes more severe than we expect. These effects are also greatly varied with the type and duration/extent of stresses and also depend on the plant species and genotypes (Pandey 2015). Therefore, it is very difficult to generalize the common effect of abiotic stress in plants. However, the major effects of abiotic stress in plants includes loss of seed germination, growth inhibition, disruption of energy assimilation and photosynthesis, imbalance in metabolism, imbalance in nutrient homeostasis and nutrient uptake, reduction of crop yield, and deterioration in crop quality (Fig. 10.1). One of the most common effects of abiotic stress in plants is oxidative stress which is described separately in a section later in this chapter.

10.3 Plant Responses to Abiotic Stresses

10.3.1 Salinity

Among these abiotic stresses, salinity/salt stress is considered as one of the most destructive stresses which reduces the land area and production of crop (Yamaguchi and Blumwald 2005; Shahbaz and Ashraf 2013). Salinity has terrible effects on the germination, vigor, and yield of the crop (Munns and Tester 2008). Genotype, growth stage, intensity, as well as duration of stress are some of the most important factors which are accountable for the response of the plant to salt stress. When plant exposed to high salinity, it suffers from osmotic stress, ionic specificity, nutritional and hormonal disorders, changing metabolic and physiological processes, and finally oxidative damage (Munns 2002; Zhu 2007). Cellular membrane disorder, photosynthesis reduction, different toxic metabolite synthesis, nutrient unavailability, and ultimate plant death are some common consequences of salt stress in plants (Mahajan and Tuteja 2005). Thus, there are three main ways of affecting plants through salt stress, e.g., by developing osmotic stress through the reduction of soil water potential, creating the ionic imbalance within the cell, lowering the concentration of some ions specially potassium (K^+) and calcium (Ca^{2+}), and ultimately causing sodium (Na^+) and chloride (Cl^-) ions' toxicity. Under salt stress, increased Na^+ interferes with K^+ uptake which is very much important for protein synthesis by acting as binding material, and thus insufficient concentrations of K^+ reduces the protein synthesis (Blaha et al. 2000). Increased Na^+-K^+ ratio and reduced K^+ availability result in the disruption of many enzymatic processes. Two major stresses called osmotic and ionic stresses are associated with salt stress. A usual response of plant to salt stress is growth inhibition which is caused by the changing concentration of soluble salt and osmotic potential of soil solution (Tavakkoli et al. 2011). Plant exposure to salt stress causes inhibition of water uptake and decreases cell expansion and lateral growth due to immediate osmotic stress occurring in the root medium (Munns and Tester 2008). Under salt-induced osmotic stress, development of shoot is severely affected compared to the root. Slower and reduced development of leaf area compared to root might be the reason behind it (Munns and Tester 2008). Impaired chlorophyll (chl) synthesis due to Cl^- ion results in the chlorotic toxicity. Significant reduction of growth and water use efficiency are also resulting from the excess accumulation of Cl^-. Germination is one of the most important phases of plant life cycle determining the final plant density. Germination and establishment of seedling are reported to decrease by salinity and considered as one of the major problems of the salt affected area. Salinity directly acts as a limiting factor for seed germination by delaying the germination time and reducing the final germination percentage and also limiting plant growth (Rahman et al. 2000). Extended salinity inhibited seed germination, while a dormant state was observed when seeds were subjected to lower level of salt stress (Khan and Weber 2008) and it was also revealed that germination process inhibited by salt stress due to lower osmotic potential of the growth medium. Salt stress also negatively affects the metabolism of nucleic acid (Gomes-Filho et al. 2008), proteins (Dantas et al. 2007), and seed food reserve utilization (Othman et al. 2006). An experiment was conducted by Kaveh et al. (2011) with *S. lycopersicum*, and he found significantly reduced germination when subjected to salinity. The gradual retardation and reduced germination of *Hordeum secalinum* were observed with an increase in NaCl concentrations. It was also concluded that 40% and 38% reductions in germination rate occur when treated with 400 and 500 mM NaCl, respectively (Lombardi and Lupi 2006). Bordi (2010) reported that different levels of NaCl treatments significantly reduced the germination percentage of *B. napus.* Some probable reasons of above-mentioned germination inhibition caused by salt stress are ionic imbalance, osmotic stress, and reduced seed water uptake. A study with four rice cultivars also showed remarkable germination reduction when subjected to different salinity levels, and germination was also more significantly reduced in sensitive cultivar compared to tolerant one (Hasanuzzaman et al. 2009). Salt stress primarily affects plant by reducing the rate of the plant growth. Firstly, the water uptake capacity of the plant is reduced, and thus growth rate of plant also reduced quickly due to salinity. There are two phases involved in the salt-induced growth reduction. Osmotic stress is the reason behind the first-phase growth reduction, and second phase of growth reduction is caused by excess accumulation of salt and its toxicity to plants (Munns 2002). The second one ultimately affects the yield by decreasing the supply of photosynthate in plants and causing death of leaves. Delayed flowering and reduced crop yield are the results of this growth reduction caused by salt stress (Munns and Tester 2008). Moreover, alteration of plant water relation also caused by salinity resulting in cell turgor loss. At the same time, water uptake becomes more difficult because of the more negative water potential caused by increased salts present in the root zone (Munns 2002). Stomatal closure is one effective strategy of osmotically stressed plants for managing loss of water (James et al. 2008). Reduction in CO_2 uptake and restricted carboxylation reaction of leaf are executed by closing of stomata. Therefore, the reduction of carbohydrate production takes place during photosynthesis which negatively influences the plant growth and crop yield. The reduction of photosynthesis along with the reduced chl *a*, chl *b*, and carotenoid (Car) pigments were observed under salt stress in rice (Amirjani 2011), mustard (Ahmed et al. 2012), and many other crops (Hasanuzzaman et al. 2012a). Plants when under salt stress become unable to take nutrients and water from the soil due to physiological drought, reduces cell expantion, leaf growth, stomatal closure, and photosynthesis as well. Salt stress causes the premature yellowing, senescence, and ultimate death of the older leaf tissues resulting from the increased concentration of toxic ions which adversely affects photosynthesis (Munns 2002; Munns and Tester 2008). Thus, reduced photosynthesis is a remarkable effect of salt stress (Leisner et al. 2010; Raziuddin et al. 2011). Higher Na^+ and K^+ toxicity in chloroplasts also inhibits the photosynthesis process. It has been revealed that salinity involved a positive growth inhibition which is associated with a marked inhibition of photosynthesis (Fisarakis et al. 2001). Again, salt stress may affect carbon metabolism or photophosphorylation (Sudhir and Murthy 2004). High salt stress remarkably hinders crop yield due to impaired growth and physiological development. In *Vigna radiata*, reduction in pod per plant, seed per pod, and seed weight was observed under high salinity (Nahar and Hasanuzzaman 2009). However, plant tolerance to salt stress is a complicated process, and it depends on the plants age, growth phase, and environment. To endure the stress of salinity, plants have developed well-organized adaptive features at the biochemical level and have antioxidant defense system to fight against the adverse condition. Usually, under salt stress, plants accumulate osmoprotectants of different types like proline (Pro), betaines, glycerols, sucrose, trehalose, etc. (Budak et al. 2013). The mechanisms how plant responds to salt stress are very complex and are still a matter of further research. It is an urgent task for the plant biologists to explore the possible ways of alleviating the damaging effects of salt stress.

10.3.2 Drought

Drought stress remained the greatest constraints for plant productivity throughout the world due to the increasing shortage of water. Drought stress limits plant growth significantly though the reduction of plant growth depends upon the degree of osmotic stress, stages of crop growth, and cultivar (Budak et al. 2013). Reduction in root and shoot growth is greater in susceptible soybean genotype because tolerant genotype can hold much water than susceptible one (Hossain et al. 2014). A study on growth of six bedding plants under drought stress revealed that plant dry weight, leaf area, and plant height differ significantly depending on species. Here, a significant reduction was observed in dry weight of *Cineraria maritima* L, *Petunia x hybrida*, and *Plumbago auriculata* under water-deficit condition, whereas leaf area reduced in *Plumbago* and plant height reduced in *Plumbago* and *Vinca* compared to control (Niu et al. 2006). Sapeta et al. (2013) reported the growth (stem diameter, stem length, leaf number, etc.) of two *Jatropha curcas* was reduced due to drought stress. Similarly, upon rehydration both genotypes showed tolerance to drought. In another study, two varieties of barley exposed to drought (50% field capacity, FC) showed significant reduction in leaf area and leaf appearance rate (Thameur et al. 2012). Reduction in water uptake and energy supply, impaired enzyme activities, loss of turgor, and reduction in cell division and expansion are considered as reasons for inhibited growth under water shortage condition (Taiz and Zeiger 2006; Hasanuzzaman et al. 2014c). Photosynthesis, the most sensitive physiological process to dehydration, is considered as physiological basis of crop yield (Luo et al. 2016). Several factors influence photosynthesis such as leaf area, stomatal opening and closure, water status in the leaf tissues, rate of CO_2 assimilation, electron transport and CO_2 assimilation reactions, and ribulose bisphosphate (RuBP) generation. Alteration in any of these factors upon dehydration condition affects photosynthesis (Ahmad et al. 2014; Hasanuzzaman et al. 2014b). The reduction in photosynthesis under deficit soil moisture condition in potato is due to stomatal closure, reduction in CO_2 assimilation, and excess production of ROS (Li et al. 2015; Obidiegwu et al. 2015). Comparative study between two maize cultivars revealed that photosynthetic activity was higher in drought-tolerant maize cultivar Giza 2 than susceptible Trihybrid 321 cultivar under water shortage condition (Moussa and Abdel-Aziz 2008). Reduction in photosynthetic pigments, changes in gas exchange characteristics, damage to photosystems, and reduced activity of enzymes related to photosynthesis are the common responses under water shortage condition and thus affect photosynthesis (Ashraf and Harris 2013). Marcińska et al. (2013) reported the reduction in chl content and photosynthesis under drought stress in wheat. Accumulation of compatible solutes is a common response of plant under water shortage condition. Sugar, sugar alcohol, glycine betaine, amino acids, and Pro are common compatible solutes in plant involved in osmotic adjustment, ROS scavenging, and protection in protein and cell structure (Budak et al. 2013). In recent years, Pro, glycine betaine, and total free amino acids were found to be increased in plant under dehydration condition to maintain leaf turgor and to improve water uptake in drying soil (Ajithkumar and Panneerselvam 2013). Water shortage significantly affects water relation in plants. Water relation can be understood by some attributes such as relative water content (RWC), leaf water potential, and transpiration rate (Nahar et al. 2017).

10.3.3 Waterlogging

Among the abiotic stresses, excess water or flooding that causes submergence or waterlogging conditions is also harmful and even lethal for plant (Nishiuchi et al. 2012). Submergence is the condition when a plant is completely covered with water or remain under water and subjected to anaerobic from aerobic condition (Jackson and Ram 2003; Nishiuchi et al. 2012). In anaerobic submerged condition, plants also subject to other secondary stresses such as low light, impaired gas exchange, and unavailability of plant nutrients (Ram et al. 1999). On the other hand, water logging is the condition of soil when excess water limits gas diffusion in plant root zone (Setter and Waters 2003). Excess water or waterlogging condition caused by heavy rainfall, poor drainage, and irrigation practices subjected plants in complex changes in several environmental parameters and plant suffered from deficiency of oxygen, light, and nutrient. Deficiency of oxygen occurred by waterlogged condition due to limited gas diffusion and rapid consumption of oxygen by soil microorganism leads to hypoxia and progressively to anoxia within few hours. Due to hypoxia or anoxia, one of the immediate responses of water logging is closing of stomata to avoid water loss that inhibits respiration (García-Sánchez et al. 2007). Inhibited respiration consequently downregulates photosynthetic machinery which decreases chl content (Damanik et al. 2010). Water logging and submergence also decrease leaf water potential, stomatal conductance, and gas exchange which also decrease photosynthetic pigment (Arbona et al. 2008). In addition, under submerged condition, due to oxygen shortage, plant accumulates volatile ethylene which has both toxicity and signaling effect (Steffens et al. 2011). Although the mechanism is still unclear, hypoxic condition also results in oxidative stress through overproduction of ROS (Kumutha et al. 2009; Sairam et al. 2011).

Excess water damages most crops with exception of rice and some other aquatic plants (Bailey-Serres and Colmer 2014). Compared with other plants, rice has some adaptive potentiality for submergence tolerance like formation of aerenchyma and leaf gas film which contribute internal aeration during submergence. Besides these, tolerant rice cultivars survive under complete submergence using special strategies of growth control, namely, quiescence and escape strategy. Though rice can be grown well under flooded and waterlogging conditions, it is not well adapted to sudden and total submergence when sustained for several days (Nishiuchi et al. 2012; Jackson and Ram 2003). The visible injury symptoms in rice seedlings appeared with faster elongation of pseudostem and yellowing of older leaves (Jackson and Ram 2003). Banerjee et al. (2015) showed some biochemical changes in rice seedlings under submergence condition (7 days) like decrease in lipid peroxidation and increase of protein oxidation, phenol content, and flavonoid content. Rice seedlings are also damaged by oxidative stress in post submergence condition due to massive oxygen burst and higher light intensity relative to submerged conditions. At recovery stage, Ella et al. (2003) showed higher lipid peroxidation and lower chl content in rice seedlings after 7 days of submergence. Short-term (24 h) water logging condition in wheat induced transient N deficiency which reduced growth and yield (Robertson et al. 2009). After 72 h of waterlogging at three-leaf and jointing stage, growth and yield attributes of summer maize decreased in field condition (Ren et al. 2014).

Kumutha et al. (2009) observed higher lipid peroxidation and growth inhibition in pigeon pea seedlings due to activation of DPI-sensitive NADPH oxidase under 4 days of waterlogging condition. It also produced smaller and chlorotic leaves which senesce earlier. Kumar et al. (2013) studied the physiological and morphological response of tolerant and sensitive cultivars varies in *V. radiata* after 3, 6, and 9 days of waterlogging. Growth inhibition and yield reduction were higher in sensitive cultivar (Pusa Baisakhi & MH–1 K–24) compared to tolerant cultivar (T 44 & MH–96–1) because of poor maintenance of leaf respiration rate and lower formation of adventitious root. Waterlogging and post-waterlogging condition induced oxidative stress and decrease photosynthetic rate in citrus seedlings (Hossain et al. 2009).

10.3.4 High Temperature

Increasing global temperatures in last few decades is responsible for severe crop loss in different countries throughout the world (Long and Ort 2010). Global temperature is expected to increase up to 2.5–5.4 °C by year 2100 (Ciscar 2012). Intensity, duration, and the rate of increase of temperature are important factors to create damage effects on plants (Wahid et al. 2007). Reduced germination and biomass, increased tillering, chlorosis, necrosis, early senescence of floral bud, premature death, and senescence of fruit are some common damage effects of high temperature (HT, Wahid et al. 2007). Heat stress during seed development results in structural disintegration and physiological disorders which further reduces germination and vigor, emergence, and seedling establishment (Akman 2009). High temperature hindered seed germination in rice by reducing a group of proteins involved in methionine metabolism, amino acid biosynthesis, energy metabolism, reserve degradation, and protein folding (Liu et al. 2014). Germination of maize is inhibited beyond 37 °C due to mutilation of protein synthesis whereas coleoptile growth is completely stopped at 45 °C (Riley 1981; Akman 2009). Increase of soil temperature beyond 45 °C causes germination failure and epicotyl emergence in sorghum (Peacock et al. 1993). In tomato, seedling emergence stops beyond 30 °C (Camejo et al. 2005). In rice, between 15 and 37 °C germination was 90%. But no germination occurred at 8 and 45 °C (Hartmann et al. 1997). Seed germination of *Phacelia tanacetifolia* inhibited by 2.7%, 5.8%, 84.0%, 89.0%, and 91.5% at temperatures of 20, 25, 30, 35, and 40 °C, respectively, compared to 15 °C (optimum for germination) (Tiryaki and Keles 2012). Lack of plasma membrane reorganization, cytoplasmic ion channel maintenance, and inhibition of the reactivation of the metabolic processes for mobilization of ions from a bound to a free form are responsible for germination reduction under HT in *Phacelia* seeds (Pirovano et al. 1997). High temperature adversely affects soil-plant- water relation, nutrient uptake, photosynthesis, transpiration, and respiration, disrupts source/sink balance, and hinders translocation of assimilate. As a result, growth and development are negatively affected (Prasad et al. 2011). Plants suffer from HT damages are often characterized by decreased water content and accumulation of osmoprotectant molecules. High temperature reduced water content in trifoliate orange seedlings (Fu et al. 2014). An increase of Pro level was noticed in transgenic plant grown under HT condition (Cvikrová et al. 2013). High temperature (31/18 °C and 34/22 °C, day/night) was found to decrease total dry weight and harvest index in wheat (Prasad et al. 2011). Enzymes are thermolabile. Catalytic properties of most enzymes are lost because of which denature of enzyme under HT. Biosynthesis of proteins and enzymes are hampered under HT. Severe HT results in complete denaturation of protein, enzymes, and membrane function and causes cell death (Allakhverdiev et al. 2008). Structural disorganization of thylakoids and swelling of stromal lamellae are HT-induced damages (Zhang et al. 2005). Chlorophyll content decreased by 19% in wheat subjected to HT (31/18 °C and 34/22 °C, day/night) (Prasad et al. 2011). Increase of temperature from 22 to 32 °C decreases photosynthesis rate and transpiration (Zhang et al. 2010). Solubility of oxygen increases more compared to carbon dioxide under HT. Oxygen becomes more concentrated for which oxygenation of RuBP occurs at HT that is termed as photorespiration. Under HT stress, gross photosynthesis is inhibited but respiration and photorespiration increase for which net photosynthesis decreases (Allakhverdiev et al. 2008; Mittler et al. 2012). As HT stress continues with decreasing net photosynthesis, plant begins to use up carbohydrate reserves that cause growth reduction. Inhibition of photosynthesis during HT stress is related to reduction of activity of RuBisCo (Allakhverdiev et al. 2008). The functioning of photosystem II (PS II) is inhibited by HT (Mittler et al. 2012) due to decrease of electron transport, removal of external proteins, and release of calcium and magnesium ions from binding site (Wahid et al. 2007; Zlatev and Lidon 2012). The singlet oxygen is overproduced under HT that damage D1 and D2 proteins (Yoshioka et al. 2006). HT restricts conversion of photosynthetic assimilates into starch that ultimately hampers grain development of cereal or seed development of legume (Stone and Nicolas 1994). Reproductive development has been long recognized as extremely sensitive to heat stress and most important reason for decreasing plant productivity (Thakur et al. 2010). The male gametophyte is more sensitive to HT in contrast to pistil or the female gametophyte (Hedhly 2011). In tomato flowers due to reduction of anthers and pollen viability, the successful fertilization is seriously hampered which further hinders development of the embryo (Barnabás et al. 2008). High temperature reduced soluble sugars in the anther and pollen grains which decreased pollen viability (Ismail and Hall 1999). In barley and *Arabidopsis*, anther development is hampered under HT (30–35 °C) due to arrest of cell proliferation, anomalous vacuoles, and mitochondrial and chloroplast development (Sakata et al. 2010). Decrease of water use efficiency during reproductive development of wheat results in decrease of photosynthesis and leaf area. As a result grain weight and sugar content of kernels decreased (Shah and Paulsen 2003) which also modulated nutritional flour quality (Hedhly et al. 2009). High-temperature stress adversely affects xylem and phloem loading which reduces water transportation and nutrient uptake (Taiz and Zeiger 2006). High-temperature stress (38 °C, 4 days) significantly increased the transpiration rate of tomato plant (Cheng et al. 2009). Increases of temperature may result in yield reduction between 2.5 and 10% in different agronomic species throughout twenty-first century (Hatfield et al. 2011). A decrease of 6.7–10% yield in rice (Peng et al. 2004; Lyman et al. 2013) and 10% reduction of yield in wheat (You et al. 2009) has been predicted with increase of 1 °C temperature in growing periods. Maize pollen viability decreases in temperatures above 35 °C (Dupuis and Dumas 1990). High temperature above 30 °C decreased seed production in soybean (Lindsey and Thomson 2012) and common bean (Porch 2006) grown in tropical humid regions. Seed set on male-sterile, female-fertile soybean plants decreased when day time temperature increased by 30–35 °C (Wiebbecke et al. 2012). In *Citrus sinensis*, temperatures higher than 30 °C increased fruit drop (Cole and McCloud 1985). In wheat, HT (31/18 °C and 34/22 °C, day/night) reduced grain numbers by 56% and individual grain weight by 25% which decreased grain yield significantly (compared to control temperature, 24/14 °C) (Prasad et al. 2011). Failure of fertilization, reduced panicle size, and damaged floral primordia were correlated to 54–64% loss in seed set in sorghum (Jain et al. 2007).

10.3.5 Chilling

In general, chilling stress indicates the low-temperature injury without forming ice crystals, and freezing stress indicates injury due to ice formation within plant tissues. Tolerance to chilling or freezing stresses is dependable to plant species. Chilling temperature reduces crop productivity by affecting several aspects of plant growth and developmental processes (Sanghera et al. 2011). Early growth stages of plant are often adversely affected by chilling stress. Optimum temperature range for germination of rice seed is 20–35 °C. According to Yoshida (1981), the temperature of 10 °C is minimum critical value, and below this temperature, rice seeds did not germinate. In *B. napus*, for 50% germination, it took 3 days at 8 °C, whereas it took 13 days at 2 °C (Angadi et al. 2000). The maximum seed germination and vigor index was reported in *T. aestivum* plants at 20–30 °C, compared to the temperature below 20 °C (Buriro et al. 2011). *Gossypium hirsutum* exposed to low temperature (LT) below 20 °C showed delayed and reduced germination (Krzyzanowski and Delouche 2011). In *T. aestivum*, the germination was drastically reduced at temperature below 8–10 °C (Zabihi-e-mahmoodabad et al. 2011). Chilling temperature causes seedling growth inhibition and abnormal phenotype of seedlings including stem discoloration, leaf yellowing or whitening, white patches/spots, withering, and reduced tillering at their vegetative stage (Nahar et al. 2012). Seedling growth and dry weight of mung bean seedlings decreased under chilling temperature (6 °C). These seedlings also showed abnormal phenotypic appearance (Nahar et al. 2015b). Nahar et al. (2009) observed cold (11 °C) injury symptoms in rice. Stunted growth, leaf chlorosis, irregular number of tiller, and malformed and discolored grain symptoms were commonly observed in chill affected rice plant. Lower temperature reduced growth duration, decreased biomass accumulation, and harvested index, seed number and seed weight of soybean (Calviñoa et al. 2003). Male gametophyte developmental process, meiosis, and tapetal hypertrophy are distorted under chilling stress. Pollen grain becomes distorted and short, anther protein degrades, and pollen tubes are deformed under chill temperature which causes pollen sterility. Fertilization and further development of fruit and seed are hampered due to chill-induced inhibition of male and female gametophyte development which is mainly due to reduced size of reproductive organs and anomalous structures of embryo sac (Jiang et al. 2002). Delayed flowering, bud abscission, sterile flowers, aborted embryo, and unfilled grain are evident in chill affected rice and other grain crop (Jiang et al. 2002; Thakur et al. 2010). Low temperatures (−2° to −5.5 °C) reduced the number of flower bud in *Simmondsia chinensis* (Nelson and Palzkill 1993). Premature flowering development in Chinese cabbage is increased by chilling temperature (Kalisz and Cebula 2001). Distorted panicle initiation and emergence, delayed heading, and sterile and malformed spikelet were noticed in rice genotypes under chilling stress of 11 °C (Nahar et al. 2009). Delayed flowering, delayed blooming, and higher rate of pollen shed and pod abortion were noticed in different genotypes of canola under chilling stress (Miller et al. 2001).

Chilling temperature damages cell membrane by protein denaturation, disrupting protein lipid structure and precipitation, and disrupting membrane permeability (Wang and Li 2006). Chilling stress thus converts the membrane into solid gel phase. Ion leakage, imbalanced anion/cation exchange, disruption of anions and cataions homeostasis, disruption of osmosis, and diffusion processes become the fate of chill affected plant (Farooq et al. 2009). Chill temperature inhibits photosynthesis due to disruption of thylakoid membrane and chloroplast structure. Electron transport, carbon cycle metabolism and stomatal conductance are hampered by chilling temperature. The PS II is considered as the primary target of chill-induced damage. Chilling temperature highly decreases the quantum efficiency of PS II. Chilling temperature restricts RuBisCO regeneration and confines the photophosphorylation (Allen and Ort 2001). Total chl content reduced by 50% in rice due to exposure to LT (15/10 °C, 14 days) (Aghaee et al. 2011). Total chl ($a + b$) of mung bean plants reduced by 32% and 38%, after 2 and 3 days of chilling temperature (6 °C) exposure, respectively, compared to the control seedlings (Nahar et al. 2015b). Wheat plants exposed to chill temperature of 3 °C (for 48 and 72 h) showed decreased chl, CO_2 assimilation, and transpiration rates (Yordanova and Popova 2007). Dehydration stress may also result from freezing of cell constituents, solutes, and water (Yadav 2010). In temperatures below 0 °C, ice formation is started in intracellular spaces that are also the vital reason for hindering the solute transportation (Thomashow 1999; Yadav 2010). Damaging the root system chill temperature reduces water and nutrient uptake and causes dehydration and osmotic stress (Chinnusamy et al. 2007). Damaged root system and stomatal closure were described as cause of chill-induced dehydration stress (Yadav 2010). Cucumber root showed chill-induced damage in cortical cells. Chill temperature also increased density of cytoplasm and damaged the endoplasmic reticulum (Lee et al. 2002). Decreased root hydraulic conductance, leaf water, and turgor potentials are common effects of chill temperature in sensitive plants (Aroca et al. 2003). During chill-induced dehydration, stress plant metabolic functions are altered which include accumulation of enzymes and isozymes (Hurry et al. 1994). Low-temperature-induced yield reduction is a common occurrence to plants due to its adverse effects on vegetative and reproductive phases (Nahar et al. 2009; Kalbarczyk 2009; Riaz-ud-din et al. 2010). In rice, chilling temperature significantly reduced yield which was due to flower abortion, pollen and ovule infertility, distorted fertilization, poor seed filling, and seed setting (Thakur et al. 2010). Other study revealed that chilling temperature reduced yield by 30–40% in temperate regions (Andaya and Mackill 2003). Rice varieties of BRRI dhan46 and BRRI dhan31 showed 16 and 37% yield reduction, respectively, due to late sowing mediated chilling stress (Nahar et al. 2009). Low temperature induced anomalous seed structure in *B. napus* and *B. rapa*. Low temperature reduced diameter and created white patches, white reticulation, red-brown pigmentation, folded seed, and shriveled seed (Angadi et al. 2000). Seed weight in *G. max* plants decreased by 5% under chill temperature of 13/23 °C (day/night) as reported by Rasolohery et al. (2008). Chilling stress of 11 °C caused yield reduction in maximum genotypes of rice, and only 23 genotypes were screened out among the 244 genotypes which showed higher yield and had better phenotypic appearance in terms of vegetative and reproductive development (Nahar et al. 2009).

10.3.6 Toxic Metals

World population is increasing day by day together with fast industrialization. As a result, big amount of toxic metals is turned out and enter into the environment (Sarma 2011). Increasing environmental pollution caused by toxic metals is becoming a significant problem in the modern world (Sun et al. 2005). Nowadays, losses in agricultural yield are very common because of soil contamination by toxic metals, and it is a serious threat for wildlife and humans health (Sharma and Dubey 2007; Sharma and Dietz 2008). Due to high reactivity of toxic metal, they can easily influence growth, development, and energy synthesis processes of organisms. So, metal toxicity is one of the key abiotic stresses leading to dangerous health effects in plants and animals (Maksymiec 2007). Excessive toxic metal uptake may occur by plants, which possibly will part take in many physiological and biochemical reactions of plants that will be able to break the normal growth of the plant by upsetting absorption, translocation, or their synthetic processes (Hasanuzzaman and Fujita 2012a,b). Plant suffered a lot by toxic metal/metalloids from germination to final seed yield. Seed germination is the primary stage of plant life, and so it is very sensitive to many environmental stresses. Germination of seeds of *Salicornia brachiata* was affected badly by different doses of Cd, Ni, and As (Sharma et al. 2011). In addition, some scientists reported that growth of seedling is very susceptible to heavy metals (Hg, Pb, Cu, Zn, etc.) in comparison to germination of seed, while Cd is the exception, because it disturbed both processes at same concentrations (Li et al. 2005). Different toxic metal/metalloids cause oxidative stress in plants. The generation of ROS is the primary response of plants under metal stress. A variety of metals can directly generate ROS through

Haber-Weiss reactions. Moreover, ROS overproduction and oxidative stress occurrence in plants may occur due to indirect consequence of heavy metal toxicity (Wojtaszek 1997; Mithofer et al. 2004). Lipid peroxidation of cells is the most detrimental effects under heavy metal stress, which can cause biomembrane deterioration directly. Hasanuzzaman et al. (2012b) observed that Cd stress (1 mM $CdCl_2$, 48 h) increased malondialdehyde (MDA) content by 134% and H_2O_2 content by 60% in rapeseed seedlings. Toxic metals/metalloids also altered the activities of antioxidant enzymes of plants as reported by several researchers. Nahar et al. (2016) reported that Cd stress in mung bean plants reduced growth, damaged chl, decreased leaf RWC and altered proline (Pro), and enhanced oxidative damage [lipid peroxidation, H_2O_2 content, $O_2^{\bullet-}$ generation rate] by disrupting activities of nonenzymatic (AsA and GSH) and enzymatic [catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), glutathione reductase (GR), mono dehydro-ascorbate (MDHAR), dehydroascorbate reductase (DHAR), glutathione peroxidase (GPX), and glutathione S-transferase (GST)] antioxidants. Similar kinds of physiological disorders were observed in rice plant under Cd stress (Rahman et al. 2015) and wheat plant under arsenic (As stress) (Hasanuzzaman and Fujita 2013).

10.3.7 Ozone

Ozone (O_3) is a heterogenous air pollutant framed in the troposphere layer. In presence of sunlight, O_3 is developed due to oxidation of oxides of nitrogen, volatile organic hydrocarbons, and carbon monoxide those generate primarily from gas motors and burning/blazing of other fossil fuels (Kesselmeier and Staudt 1999). Expanding levels of surrounding ozone may force destructive impacts on human, animals, and plants. The harming influence of O_3 to plant species might be acute or chronic. Acute damage is created by a high concentration of O_3 (>150 ppb) inside a brief timeframe (Gillespie et al. 2011) and brought about foliar injuries and impels an array of biochemical and physiological reactions in plants (Tsukahara et al. 2015). Chronic damage to lower O_3 concentrations is portrayed by decreasing growth and development without noticeable harm (Gillespie et al. 2011). Crops demonstrate differential intra and interspecific phenotypic responses to O_3 (Biswas et al. 2008; Brosche et al. 2010). The obvious indications of O_3 damage have been evaluated in foliage part. Chlorotic or necrotic injuries on leaves, reduced biomass production, and yield reduction are common consequences of O_3 stress (Wilkinson et al. 2012). The reproduction process of plants is greatly hampered due to exposure of tropospheric O_3. Grain characteristics of rice, wheat, and maize crops are negatively affected under O_3 stress (Biswas and Jiang 2011). It is estimated that elevated O_3 can reduce grain yield of different rice cultivars by 4.2–5.2% (Sawada et al. 2016) and yield of soybean by 23–27% (Wang and Mauzerall 2004). The fruits of different types of plants are affected differentially under O_3 stress. Pod development is adversely affected by O_3 which results in reduction of number and size of pod. Tuber number and yield have been demonstrated to decrease as affected by O_3 in tuber crops (Wilkinson et al. 2012). In potato, tuber number and total tuber yield decreased by 38% and 45%, respectively, due to exposure of O_3 (Foster et al. 1983). Pollen germination and tube development are adversely affected by O_3; abscissions of bud or flower and individual ovules or seeds are commonly occurred phenomenon under O_3 stress (Black et al. 2000).

10.3.8 Ultraviolet Radiation

Solar radiation supplies the essential energy for growth and development of plant via photosynthesis but high light and particularly its integral ultraviolet (UV) fraction cause stress potentially leading to severe injury to cellular components of plants even the DNA and proteins (Müller-Xing et al. 2014). The ultraviolet radiation from sunlight is divided into three broad classes: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (280–100 nm) light. UV-A and UV-B can easily reach to the surface of earth, but UV-C is filtered out in the atmosphere (Biedermann et al. 2011). Stratospheric ozone layer does not affected by the UV-A, because it is not attenuated by ozone layer. The wavelength of UV-C is shorter than 280 nm, and it cannot arrive at ground level, and this is not expected to change. The UV-B radiation gets top most importance by the researcher and geologist, because ozone absorbed it. Among UV radiation types, even though UV-B is only a negligible constituent of the total solar radiation (less than 0.5%), due to its high energy, its potential for causing biological damage is remarkably high, and even little raise could lead to considerable biological damage (Zlatev et al. 2010). Due to large-scale production of anthropogenic pollutants, intensities of UV-B radiation in the sunlight are slowly increasing in the world as a result of depletion is going on in the stratospheric ozone layer. Previous research on UV-B radiation confirmed that it has significant photobiological consequences on growth, development, and other biochemical activities of plants (McNamara and Hill 2000). The intensities of UV-B vary with the angle of sun and thickness of stratospheric ozone layer. So, all organisms of the earth are exposed to UV-B radiation in different intensities. The rate of enhance UV-B intensity depends on latitude, and higher amount of UV-B is recorded in antarctic and arctic regions (Zlatev et al. 2010).

Frequent discharge of chlorofluorocarbons and other pollutants due to anthropogenic activities is increasing the amount of ultraviolet radiation in the earth surface which is the main reason of stratospheric ozone layer depletion (Dai et al. 1997; Sharma et al. 1998). The stratospheric ozone depletion and increased solar UV radiation cause injury to plants and animals (Costa et al. 2002; Ravindran et al. 2010). Sunlight is obligatory for photosynthesis of terrestrial plants, so they are mostly vulnerable to UV radiation (Greenberg et al. 1996; Sharma et al. 1998). The UV-A radiation shows less harmful effect to organism among all the UV radiations. In addition, also UV-C radiation does not show much harmful effects on the biota because it is observed by the oxygen and ozone layer (Barta et al. 2004). The impact of UV radiation on most cultivated plants is negative and unfavorable to plant growth and development (Vyšniauskienė and Rančelienė 2014). UV radiation creates oxidative stress (Costa et al. 2002), which come up from the detrimental effects of ROS, and they react with lipids, proteins, and nucleic acid (Dai et al. 1997). Plants have many enzymatic and nonenzymatic detoxification systems under normal healthy growth condition to efficiently scavenge or detoxify the ROS or their secondary reaction products (Bartling et al. 1993). Nasibi and M-kalantari (2005) carried out an experiment regarding the action of the antioxidant defense system in *Brassica napus*, under different ultraviolet radiation (UV-A, UV-B, and UV-C). This experiment demonstrated that UV-B and UV-C radiation induced oxidative stress. Because, they increased the lipid peroxidation and total ascorbate content of cells. The treatments of UV-B and UV-C significantly increased flavonoids and anthocyanins levels compared with control and UV-A-treated plants. These compounds perform as internal filters and also have an antioxidant action against ROS such as H_2O_2. Protein content increased under UV-B and UV-C, which probably related to the synthesis of different defense proteins such as HSP. On the other hand, treatment of UV-B radiation for 8 days on maize plants (*Zea mays* L. cv. SC. 704, 21 days old) increased lipid peroxidation (MDA content) and decreased RWC. UV-B stress also increased carotenoid content and activity of some enzymes (APX and GPX) Javadmanesh et al. (2012). In addition, plants under adverse conditions decreased their protein content in root tissue but not in shoot tissue. Vyšniauskienė and Rančelienė (2014) reported that compared to the control, the plant height of early potato cultivars reduced after the UV-B exposure. However, fresh and dry weight of leaves, chlorophyll *a* and *b*, and carotenoid contents in potato cultivars remained unaffected after UV-B treatment. Antioxidative enzymes also increased due to exposure of UV-B in potato cultivars which prove the active response of plant to UV-B-induced stress. They also suggested that response and tolerance depend on the plant genotype. Similar kind of reduction in photosynthetic parameters was observed in cotton plant under UV-B stress (Reddy et al. 2003). UV radiation reduces the total mass and yield of different plants (Gao et al. 2004; Liu et al. 2013). A field experiment was carried out with three soybean cultivars [Hai339 (H339), Heinong 35(HN35), and Kennong18 (KN18)] by exposing them to higher UV-B radiation. The UV-B radiation reduced height of plant, dry weight of individual stem, and yield per plant. Pod number per plant was the most responsible component for yield change under UV-B radiation in the 2-year study. UV-B radiation reduced pod number per plant of three soybean cultivars by 43.5% for KN18, 30.4% for HN35, and 29.6% for H339. They also stated that seed number per pod was less affected than the pod number per plant under UV-B light treatment. The UV-B radiation had no noteworthy effect on effective filling period, but seed size was negatively impacted by this radiation, and it reduced 12.3% for all the cultivars of soybean. UV-B radiation decreased the cotyledon cell number, as a result seed size was decreased. No significant effect on cell volume of cotyledon, cell weight, or cell growth rate of soybean varieties was observed under enhanced UV-B radiation (Liu et al. 2013). Similarly Gao et al. (2004) reported that higher UV-B radiation caused a considerable declination in the growth, yield, and quality of maize. Besides the yield and biomass reduction, UV-B radiation altered the nutrient status of plants (Yue et al. 1998).

10.4 Abiotic Stress-Induced Oxidative Stress

Reactive oxygen species are unavoidable by-products derived from the reduction of molecular oxygen (O_2) and include some free radicals: superoxide ($O_2^{\bullet-}$), hydroxyl radical ($OH^{\bullet}$), alkoxyl ($RO^{\bullet}$), and peroxyl ($ROO^{\bullet}$) and some non-radical products, H_2O_2, singlet oxygen ($^1O_2$), etc. (Gill and Tuteja 2010; Sandalio et al. 2013). Chloroplast, mitochondria, and peroxisomes are the main source of ROS production, chloroplast being the main source (Apel and Hirt 2004). Physical and chemical activation is involved in ROS generation. Physical activation involves transfer of energy from photo activated pigment such as excited chl (chl triplet state, ^{3}chl) that involved in the transfer of its excitation energy onto O_2 to make $^1O_2$. Chemical activation involves univalent reduction of dioxygen or triplet oxygen (molecular oxygen) to water; four electrons and four protons are engaged which leave three major ROS, viz. $O_2^{\bullet-}$, H_2O_2 and •OH (Gill and Tuteja 2010; Sandalio et al. 2013). Under normal or nonstress environment, electron flow from excited PS centers is transferred to $NADP^+$ which is reduced to NADPH. This NADPH enters Calvin cycle where it reduces final electron acceptor (CO_2). Calvin cycle recycles NADP (Vašková et al. 2012). But under stress conditions, NADP recycling is impaired, electron transport chain (ETC) can be over loaded, and electron leakage from ferredoxin is converted to O_2, reducing it to $O_2^{\bullet-}$ through Mehler reaction (Elstner 1991). The $O_2^{\bullet-}$ can be converted into more reactive H_2O_2 by SOD activity in outer stromal membrane surface (Gill and Tuteja 2010). In presence of Fe^{2+}, H_2O_2 is transformed into extreme reactive OH• through Fenton reaction (at Fe-S centers) (Gill and Tuteja 2010; Sharma et al. 2012). Peroxisome metabolic processes are chiefly involved in the production of H_2O_2. The $O_2^{\bullet-}$ can also be produced in peroxisome (Noctor et al. 2002). Mitochondrial electron transport chain (ETC) is also an important source of ROS production in plant cells. Mitochondrial ETC and ATP syntheses are coupled strongly, and stress-induced imbalance between these two may lead to over-reduction of electron carriers as a result of which ROS overproduce (Noctor et al. 2007; Blokhina and Fagerstedt 2010). NADPH-dependent electron transport process is involved with Cyt P_{450} and $O_2^{\bullet-}$ generation in the endoplasmic reticulum (Mittler 2002). In cell wall, plasma membrane, and apoplastic area, ROS including $OH^{\bullet}$ and H_2O_2 can be overproduced through ranges of biochemical reactions (Heyno et al. 2011).

Under normal growing (nonstress) condition, ROS is kept in a balance state by well-equipped antioxidant defense system. In contrast, under environmental stress condition, excess ROS generation leads to oxidative stress. The ROS can cause membrane lipid peroxidation, protein oxidation, and DNA damage. Cell structure and biochemical and physiological process are disrupted by ROS-induced oxidative stress and, at extreme state, gradually lead to programmed cell death (Gill and Tuteja 2010; Hasanuzzaman et al. 2012a). ROS-induced oxidative stress is a common phenomenon under different abiotic stresses. The ROS production under salt stress might be increased by three-fold. The level of H_2O_2 can be increased by 30-fold under salt stress (Singh and Flowers 2010). Salinity-induced oxidative stress was documented in different plant species. Salt stress significantly increased H_2O_2 and MDA levels in mung bean seedlings (Nahar et al. 2014). Salt affected wheat seedlings showed high level of H_2O_2 by 60%, compared to control. Lipid peroxidation in those wheat seedlings increased by 27 and 73% at 150 mM and 300 mM NaCl, respectively (Hasanuzzaman et al. 2011a, b). Drought is one of major stresses contributing the major ROS and causing severe oxidative stress within the plants. More than 70% of total H_2O_2 were demonstrated to produce due to photorespiration under drought stress condition (Noctor et al. 2002). Cellular membrane damage was related to significant rise in $O_2^{\bullet-}$ and H_2O_2 in leaves of drought affected *Malus* spp. (Wang et al. 2012). Similar results were demonstrated in mung bean seedlings under PEG-induced drought stress (Nahar et al. 2017). High-temperature raised ROS production in wheat seedlings. The H_2O_2 contents in wheat seedlings were 0.5, 0.58, 0.78, and 1.1 μmol g^{-1} FW in response to 22, 30, 35, and 40 °C (2 h) temperature stresses, respectively (Kumar et al. 2012). Mung bean seedlings exposed drought and high-temperature stress separately or in combined increased H_2O_2 and $O_2^{\bullet-}$ production which was evidenced from higher cellular H_2O_2 and $O_2^{\bullet-}$ contents and increased number of spots of these ROS in leaves, compared to control. The H_2O_2 level, $O_2^{\bullet-}$ generation rate, lipoxygenase (LOX) activity, and MDA contents under combined HT and drought stress were 122, 146, 108, and 120%, respectively, in contrast to control (Nahar et al. 2016a). Low temperature creates imbalance between light absorption and light use due to inhibition of C_3 cycle which enhances ROS production. ROS generation also increased due to increased photosynthetic electron flux to O_2 as well as the over-reduction of respiratory ETC (Hu et al. 2008). Waterlogging or flooding induces hypoxic or anoxic environment. Under waterlogging stress, ROS can be produced when plants go through a hypoxia/anoxia from normoxic conditions and also under the condition when plants return to an aerobic environment (Irfan et al. 2010). Enhanced accumulation of H_2O_2 or lipid peroxidation under anoxic conditions was reported previously (Sairam et al. 2011). Plants under heavy metal exposure cause a significant increase of ROS production and subsequent oxidative stress. Redox-active metals such as Fe, Cu, Cr, V, and Co initiate redox reactions in the cell and directly involved in the formation of $OH^{\bullet}$ via Haber-Weiss and Fenton reactions (Sharma and Dietz 2008). Other metals also generate ROS and cause oxidative stress in different ways (Hasanuzzaman et al. 2012a; Nahar et al. 2016). Heavy metal-dependent activation of LOX also leads to lipid peroxidation (Nahar et al. 2016). Mung bean seedlings exposed Cd stress showed a higher level of ROS generation including H_2O_2 and $O_2^{\bullet-}$, a higher LOX activity, and increased lipid peroxidation (Nahar et al. 2016). Wheat seedlings exposed to As; 0.25 and 0.5 mM showed 41 and 95% increase of H_2O_2 and 58 and 180% increase of lipid peroxidation level, respectively, compared to control (Hasanuzzaman and Fujita 2013). Ozone (O_3) being strong oxidant interacts with apoplastic constituents in generating ROS (Yan et al. 2010). Different studies designated that elevated O_3 highly increased the levels of $O_2^{\bullet-}$, H_2O_2 and lipid peroxidation in plants (Yan et al. 2010; Feng et al. 2011). UV-B radiation also generates ROS and results in damage to proteins, lipids, nucleic acids, and associated enzymes (Du et al. 2011; Singh et al. 2011).

10.5 Highlights of Potent Micronutrients and Trace Elements Associated with Plants' Functions

Micronutrients and trace elements are required in small amount but equally important for plant functions as like macronutrients. Their major functions in plants are summarized in Table 10.1. Plants show some deficiency symptoms due to lack of these nutrients as shown in Fig. 10.2.

Table 10.1 Major functions of trace elements/micronutrients in plants

Elements	Functions
Copper	Essential for carbohydrate and nitrogen metabolism also plays roles in lignin synthesis for cell wall strengthening. It plays an important role in chl synthesis. It also activates some enzymes by playing role as coenzyme
Iron	It plays role in nitrogen reduction and fixation and lignin formation. Important for chlorophyll synthesis and energy transfer
Zinc	Important for energy production, formation of chlorophyll, and plant hormone like indole acetic acid (IAA). Helps in protein synthesis, better seed quality, and uniform crop maturity
Boron	Helps in carbohydrate transport, cell wall formation, pollen formation
Manganese	Important for enzyme activity and other metabolic processes. Important for nitrogen metabolism, pollen tube growth, and root hair formation
Molybdenum	Essential for pollen formation, fruit and grain formation. It can convert nitrate into usable form
Cobalt	Promotes to auxin formation and nitrogen fixation. It is also essential for the development of bud, plant stem, and coleoptiles. It also increases drought resistance to seed
Nickel	Component of some plant enzymes, most notably urease, which metabolizes urea nitrogen into useable ammonia within the plant. It plays role in root nodule growth. Essential part of glyoxalase system
Silicon	Strengthens cell walls, stimulates plant growth. Performs as essential function in healing plants in response to environmental stress
Selenium	It stimulates nitrogen assimilation and regulates the water status of plants. Acts as antioxidant and stress protectants

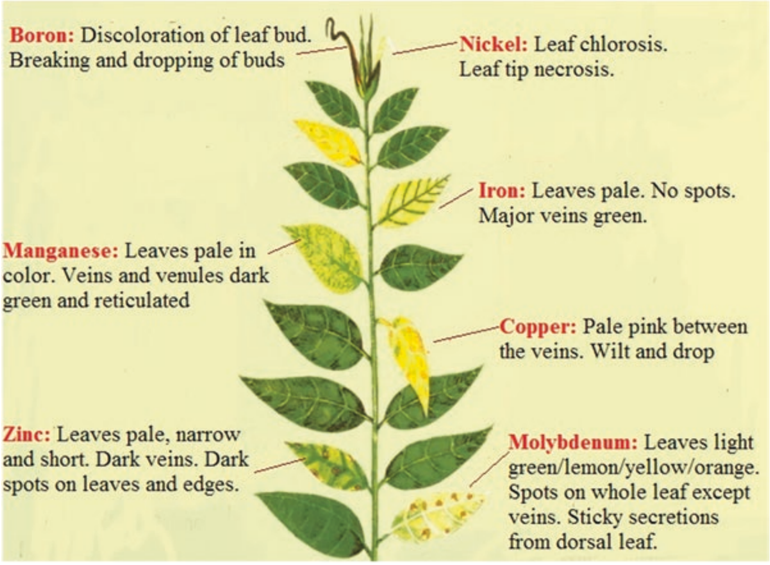


Fig. 10.2 Visualization of deficiency symptoms of major trace elements in plants

10.6 Functional Role of Trace Elements in Conferring Abiotic Stress Tolerance

Although trace elements are required in small amount, their essentialities are the same as macronutrients. Although several trace elements have not yet been identified as essential elements, they have some vital functions in plant growth and development (Fig. 10.3). In addition, these elements have specific metabolic functions and diverse roles in stress tolerance (Table 10.2). However, these elements showed toxicity in plants when exposed to high concentration.

10.6.1 Copper

Due to its presence in multiple oxidation states in vivo, Cu is involved in many physiologic conditions. The role of Cu in plants stress tolerance is well considered due to its functions as structural element of photosynthetic electron transport, cell signaling, and metabolism as well as participation in enzymatic activities (Yruela 2005). It is important that both deficiency and abundance of Cu negatively affect plant processes. For instance, photosynthetic ETC is hampered under both Cu

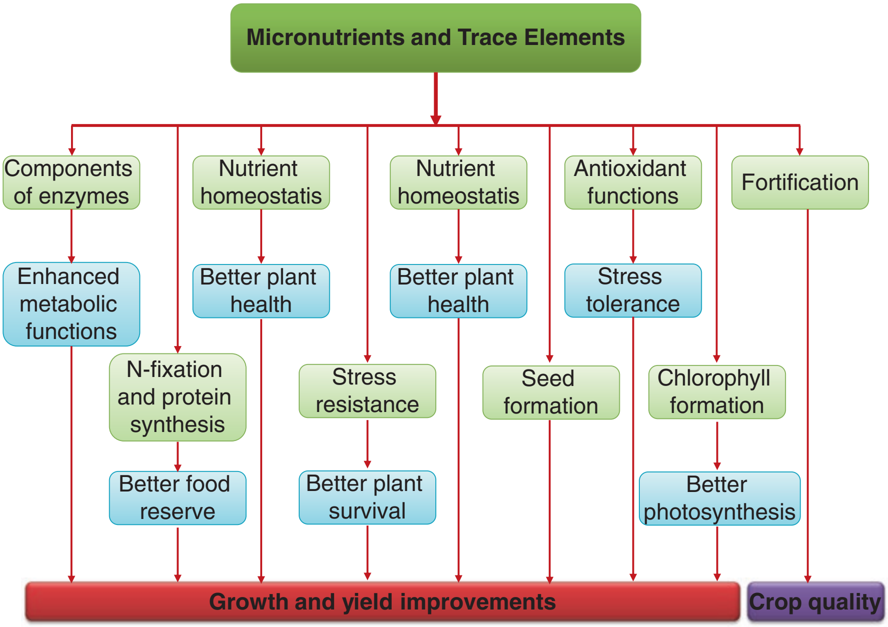


Fig. 10.3 Different aspects of the beneficial roles of trace elements in boosting plant growth, yield, and quality

Table 10.2 Beneficial effects of trace elements supplementation in plants grown under adverse environmental conditions

Plant species	Trace elements	Stress	Beneficial effects	References
Hordeum vulgare	300 µM $ZnSO_4$	0.1–10 µM $CdCl_2$ (10–22 DAS)	• Reduced Cd uptake and MDA • Increased biomass	Wu and Zhang (2002)
Capsicum annuum	2 and 10 mg $ZnSO_{4.}$ kg^{-1} soil	Salt, 0.5 and 1.5%, NaCl, 20 days	• Reduced Na uptake	Aktaş et al. (2006)
Pistacia vera	5–20 mg $ZnSO_4$ kg^{-1} soil	Salt, NaCl 0.8–3.2 g kg^{-1} soil, 100 days	• Reduced lipid peroxidation and LOX activity • Reduced electrolyte leakage • Increased phenolic contents	Tavallali et al. (2010)
Triticum aestivum	Zn and Fe	Drought, stop watering at pollination and seed-filling stage	• Increased seed yield and kernel weight	Monjezi et al. (2012)
T. aestivum	50 mg B L^{-1}	Drought, 50, 75, and 100% irrigation	• Increased chl and Car • Decreased H_2O_2 and Pro content	Abdel-Motagally and El-Zohri (2016)
T. aestivum	B (0, 0.5, 1%)	Drought, irrigation withdrawal	• Improved LAI, CGR, and NAR	Moeinian et al. (2011)
Zea mays	Foliar spray of 50 and 100 ppm boric acid	Salt, 4% NaCl	• Increased plant height, leaf number, shoot dry weight, and grain weight	Salim (2014)
Citrus grandis	2.5 and 20 µM H_3BO_3	Al stress, 1.2 mM $AlCl_3$, 18 week	• Higher dry weight, root citrate secretion, root malate secretion	Zhou et al. (2015)
H. vulgare	2.0 mmol m^{-3} Mn	Salt stress, 125 mM NaCl and 9.6 mM $CaCl_2$, 24 days	• Increased NAR, RGR, photosynthesis, Mn uptake in salt-stressed seedlings	Cramer and Nowak (1992)
H. vulgare	3 mM Mn, 1 WAS	Salinity, 8 dS m^{-1}; two weeks after sowing (WAS)	• Increased dry weight, NAR, RGR, leaf area ratio	Pandya et al. (2004)
Oryza sativa	5 and 25 µM $MnCl_2$	Cd, 5 and 25 µM $CdCl_2$, 7 days	• Increased chl, Car, AsA, and sugar content • Decreased Cd uptake, MDA content, CAT, and POD activity	Sebastian and Prasad (2015)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Z. mays	100 µM $MnSO_4$	Cd, 10 µM $CdCl_2$, 12 h	• Increased root length and decrease Cd uptake	Pal'ove-Balang et al. (2006)
Phytolacca americana	1–5 mM $MnCl_2$	Cd, 10 and 50 µM $CdCl_2$	• Increased root, stem, and leaf dry weight and decreased Cd content	Peng et al. (2008)
Camellia sinensis	50 and 100 µM $MnCl_2$	Drought, Irrigation withdrawal	• Increased dry mass and RWC, total phenolic and AsA content	Upadhyaya et al. (2012)
C. annuum	1.8 mM K_2SiO_3	Salinity, 50 mM NaCl	• Improved growth • Increased photosynthesis rate, stomatal conductance • Decreased electrolyte leakage • Decrease ROS production and lipid peroxidation • Increased activities of antioxidant enzymes	Manivannan et al. (2016)
Anethum graveolens	1.5 mM $Na_2Si_3O_7$	Salinity, 10 dS m^{-1}	• Improved growth • Increased K^+ content and reduced Na^+ content • Reduced lipid peroxidation • Increased activities of antioxidant enzymes	Shekari et al. (2015)
Z. mays	1.5 mM $Na_2O_3Si.5H_2O$	Alkalinity, 25–75 mM Na_2CO_3	• Improved growth • Enhancement in leaf RWC and levels of photosynthetic pigments • Increased soluble sugars, soluble proteins, total free amino acids and K • Enhanced activities of SOD, CAT, and POD	Latef and Tran (2016)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
O. sativa	350 kg ha^{-1} of Si fertilizer	Drought, −0.050 or −0.025 MPa	• Increased Pro content • Increased peroxidase activity	Mauad et al. (2016)
Saccharum officinarum	2 mM Ca_2SiO_4	Salinity, 100 mM NaCl	• Reduced tissues Na^+ concentration • Improved K^+ uptake, K^+/Na^+ ratios and Ca^{2+} content • Increased shoot and root dry matter	Ashraf et al. (2010)
Vitis vinifera	4 mM Si $Na_2Si_3O_7$	Salinity, 20 mM NaCl	• Reduced stomatal resistance • Reduced MDA and H_2O_2 contents • Increased APX activity	Soylemezoglu et al. (2009)
Brassica napus	2 and 4 mM K_2SiO_3	Salinity, 300 mM NaCl	• Increased leaf area, leaf fresh weight, seed yield, and photosynthesis • Increased APX and NR activities • Increased chl content	Bybordi (2012)
Z. mays	0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8, and 3.2 mM $Si(OH)_4$	Salinity, 150 mM NaCl	• Improved growth • Increased net CO_2 assimilation rate, stomatal conductance (g_s), transpiration, and leaf sub-stomatal CO_2 concentration	Parveen and Ashraf (2010)
Spartina densiflora	500 µM Na_2SiO_3	Salinity, 171 and 680 mM NaCl	• Improved growth associated with higher net photosynthetic rate, water-use efficiency, and g_s • Reduced tissue Na^+content	Mateos-Naranjo et al. (2013)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Solanum lycopersicum	2.5 mM K_2SiO_3	Drought, 10% PEG	• Improved water balance • Increased growth and photosynthesis • Decreased ROS production • Enhanced activities of SOD and CAT • Increased level of AsA and GSH	Shi et al. (2016)
T. aestivum	Si 50 mg kg^{-1} and 150 mg kg^{-1}	Drought, 50%, 75% and 100% FC	• Increased plant biomass, plant height, and spike weight • Increased tissue Si concentration and uptake	Ahmad et al. (2007)
Z. mays	0.8 mM Na_2SiO_3	Drought, 50% water deficit	• Increased dry mass, tissue nutrient content, water use efficiency • Reduced leaf wilting	Janislampi (2012)
Glycine max	1.70 mM Na_2SiO_3	Drought , −0.5 MPa	• Increased root and shoot dry matter and the ratio of root/shoot • Increased leaf water potential, growth • Increased net photosynthetic rate, *gs*, chl content • Decreased free Pro content, lipid peroxidation, and electrolytes leakage	Shen et al. (2010)
S. bicolor	200 mg L^{-1} Si	Drought, withholding irrigation	• Increased net photosynthetic rate • Decreased shoot to root ratio by increasing root growth	Ahmed et al. (2011)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Oryza sativa	1.5 mM Na_2SiO_3	HT, 39 °C	• Increased number of pollen grain those were with higher diameter • Increased anther dehiscence percentage, pollination, and fertilization	Li et al. (2005)
Z. mays	10 mM K_2SiO_3	Chilling, 2/3 ± 1 °C	• Enhanced photosynthesis • Reduced ROS production • Enhanced AsA and GSH pool	Habibi (2016)
Cucumis sativus	0.1 and 1 mM K_2SiO_3	Chilling (15/8 °C)	• Reduced leaves withering • Increased activities of SOD, GPX, APX, MDHAR, GR, GSH • Increased AsA content • Decreased levels of H_2O_2, $O_2^{\bullet -}$ and MDA	Liu et al. (2009)
T. aestivum	0.1 and 1.0 mM K_2SiO_3	Freezing, −5 °C	• Increased leaf water content • Improved activities of antioxidant enzymes AsA, GSH, SOD, and CAT • Reduced H_2O_2, free Pro, and MDA content	Liang et al. (2008)
C. limon	50, 150 and 250 mg L^{-1} K_2SiO_3	Freezing, 0.5 °C for 28 days	• Increased phenolics and flavonoids concentration • Improved fruit quality • Reduced chilling injury	Mditshwa et al. (2013)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
O. sativa	0.6 mM $Si(OH)_4$	Heavy metal (HM), 10 µM $CdCl_2$, 4 days	• Improved plant growth • Improved photosynthesis • Maintenance of nutrient homeostasis • Stimulation of the AsA-GSH pathway	Farooq et al. (2016)
S. nigrum	1.0 mM Na_2SiO_3	HM, 100 µM $CdCl_2$	• Decreased Cd accumulation • Reduced electrolyte leakage • Increased activities of SOD, POD, CAT, and APX	Liu et al. (2013)
O. sativa	1.25, and 2.5 mM Na_2SiO_3	HM, 100 µM $K_2Cr_2O_7$	• Increased seedling height, dry biomass, and soluble protein content • Reduced Cr uptake and translocation • Improved antioxidant defense	Zeng et al. (2011)
B. chinensis	1.5 mM K_2SiO_3	HM, 0.5 and 5 mg L^{-1} $CdCl_2$	• Increased shoot and root biomass • Decreased Cd uptake and root-to-shoot transport • Increased SOD, CAT, APX, reduced MDA, and H_2O_2 concentrations	Song et al. (2009)
C. sativus	1 mM Na_2SiO_3	HM, 100 µM $CdCl_2$	• Reversed chlorosis, protected the chloroplast from disorganization • Increased pigment contents, intercellular CO_2 concentration, *gs* and net photosynthetic rate • Improved water use efficiency	Feng et al. (2010)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Z. mays	1 mM Si as $Si(OH)_4$	HM, 200 or 500 μM $MnSO_4$	• Ameliorated chloroplast damage and photoinhibition • Improved detoxification and compartmentation of Mn	Doncheva et al. (2009)
Picea abies	0.2, 0.5 and 1.0 mM Si	HM, 0.2, 0.5 and 1.0 mM Al	• Ameliorated adverse effects on cell wall thickening, degree of vacuolation, and the degeneration of mitochondria, golgi bodies, endoplasmic reticulum, and nucleus • Reduced cell death	Prabagar et al. (2011)
V. vinifera	4 mM $Na_2Si_3O_7$	HM, 20 mg kg^{-1} H_3BO_3	• Reduced tissue B concentration • Increased activities of CAT and APX • Reduced Pro, H_2O_2, and MDA content	Soylemezoglu et al. (2009)
O. sativa	Si fertilizer ($CaSiO_3$) @ 40 g m^{-2}	UV-B radiation, 250–350 nm	• Improved cell walls of sclerenchyma, vascular bundle sheath, and metaxylem vessel cells, cellulose, non-cellulosic polysaccharides, lignin, and phenolic acids	Goto et al. (2003)
G. max	1.70 mM Si	UV-B radiation, 290–320 nm	• Increased root and shoot dry weight and their ratio • Increased net photosynthetic rate and *gs* • Decreased H_2O_2 content	Shen et al. (2010)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Vigna unguiculata	5–10 µM Na_2SeO_4	Salinity, 100 mM NaCl	• Improved photosynthetic pigments • Increased Pro and soluble sugar content and PAL • Improved growth and yield	Manaf (2016)
L. esculentum	5–10 µM Na_2SeO_3	Salinity, 25–50 mM NaCl	• Improved the integrity of cell membrane • Increased leaf RWC • Enhanced antioxidant defense system	Mozafariyan et al. (2016)
L. esculentum	50 µM Na_2SeO_3	Salinity, 100 mM NaCl	• Improved photosynthetic efficiency • Decreased ROS production • Enhanced antioxidant defense	Diao et al. (2014)
B. napus	25 µM Na_2SeO_4, 48 h	Salinity, 100 and 200 mM NaCl, 48 h	• ncreased AsA and GSH contents, GSH/GSSG ratio, and activities of APX, MDHAR, DHAR, GR, GST, GPX, and CAT • Reduced levels of H_2O_2 and MDA	Hasanuzzaman et al. (2011b)
C. sativus	5, 10, or 20 µM Na_2SeO_4, 11 days	Salinity, 50 mM NaCl, 11 days	• Decreased content of Cl^- in the shoots tissues • Increased Pro accumulation • Enhanced antioxidant defense • Decreased lipid peroxidation	Hawrylak-Nowak (2009)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Rumex patientia x *R. tianshanicus*	1–5 µM Na_2SeO_4, 43 days	Salinity, 100 mM NaCl, 43 days	• Stimulated growth • Increased activities of SOD and POD • Increased accumulation of water-soluble sugar	Kong et al. (2005)
S. vulgare	20 mg L^{-1} Se	Drought, 35–70% FC	• Improved growth • Increased photosynthesis • Increased yield	Aissa et al. (2016)
T. aestivum	15 µg L^{-1} Na_2SeO_4	Drought, 20% FC	• Increased dry matter accumulation • Protection of leaf photochemical event • Increased photosynthesis	Hajiboland et al. (2016)
T. aestivum	7.06 µM Se	Water deficit	• Increased stress tolerance index • Increased biomass	Nawaz et al. (2014)
Trifolium repens	5 µM Na_2SeO_4, 0–5 days	Drought, PEG 6000 (−1.0 MPa), 0–5 days	• Decreased levels of H_2O_2, TBARS, DHA, and GSSG • Increased the levels of AsA and GSH and AsA/DHA and GSH/GSSG ratios • Improved the activities of MDHAR, DHAR, and GR	Wang et al. (2011)
B. napus	15 and 30 g L^{-1} as Na_2SeO_3	Drought, limited irrigation at early stem elongation	• Increased plant height • Increased pod and seed development • Increased yield	Zahedi et al. (2009)
T. aestivum	Se (Na_2SeO_3) 0.5 mg kg^{-1}, 20 days	Drought, 30% FC	• Increased root activity • Increased Pro content • Increased activities of POD and CAT	Xiaoqin et al. (2009a)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
T. aestivum	1.0, 2.0, and 3.0 mg kg^{-1} Na_2SeO_3, 20 days	Water stress of 30% FC, 20 days	• Increased root activity • Increased chl, carotenoids and Pro content • Increased activities of POD and CAT activities • Decreased MDA content	Xiaoqin et al. (2009b)
Fagopyrum esculentum	1 g m^{-3} Na_2SeO_4, 7–8 weeks	Reduction of water by 50%, 8 weeks	• Improved *gs*, potential photochemical efficiency of PS II, respiratory potential • Increased yield	Tadina et al. (2007)
Z. mays	20 g ha^{-1}Na_2SeO_4	Drought, withholding water	• Enhanced activities of SOD • Reduced MDA content • Improved grain yield	Sajedi et al. (2011)
T. aestivum	0, 25, 50, 75, and 100 μM of Na_2SeO_4, 30 or 60 min	Drought, withholding water for 1 week	• Increased root length and total biomass • Increased stress tolerance index • Increased total sugar content and total free amino acids	Nawaz et al. (2013)
B. napus	25 μM Se (Na_2SeO_4), 48 h	Drought, 10 and 20% PEG-6000, 48 h	• Increased activities of APX, DHAR, MDHAR, GR, GST, GPX, and CAT • Decreased GSSG content, H_2O_2 • Decreased lipid peroxidation	Hasanuzzaman and Fujita (2011)
Z. mays	5–15 μM $Na_2SeO_3 \cdot 5H_2O$	Drought, 25% PEG	• Unregulated AsA-GSH cycle • Decreased ROS production	Yildiztugay et al. (2016)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Z. mays	5–15 µM $Na_2SeO_3 \cdot 5H_2O$	HT (24–44 °C)	• Upregulated AsA-GSH cycle • Decreased ROS production	Yildiztugay et al. (2016)
T. aestivum	2–4 mg L^{-1} Se	HT, 38 ± 2 °C	• Improved growth and photosynthesis • Increased yield attributes and yield • Increased nonenzymatic antioxidants • Enhanced activities of antioxidant enzymes	Iqbal et al. (2015)
S. bicolor	Na_2SeO_4 (75 mg L^{-1}), 7–28 days	HT, 40/30 °C, 7–28 days	• Increased antioxidant enzyme • Decreased ROS levels and membrane damage • Increased antioxidant defense • Increased grain yield	Djanaguiraman et al. (2010)
C. sativus	2.5, 5, 10, or 20 µM Na_2SeO_4	LT, 10 °C/5 °C for 24 h, day	• Improved shoot fresh weight • Increase of Pro content • Reduced MDA level	Hawrylak-Nowak et al. (2010)
T. aestivum	0.5, 1.0, 2.0, 3.0 mg kg^{-1} Na_2SeO_3, 72 h	LT, 4 °C, 72 h	• Increased biomass • Increased chl, anthocyanins, flavonoids, and phenolic compounds • Increased activities of POD and CAT	Chu et al. (2010)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
T. aestivum	Se (5 mg Se L^{-1}), 5, 10, and 15 h	LT, 3 or 5 °C, 14 days	• Enhanced growth • Increased chl, anthocyanin, sugar, and Pro contents • Enhanced antioxidant defense system • Decreased membrane damage	Akladious (2012)
S. bicolor	Se (3 and 6 μM L^{-1} Na_2SeO_4), 6 h	LT, 4–8 °C, 7 days	• Enhanced growth • Increased levels of chl, anthocyanin, sugar, Pro, and AsA • Increased enzymatic activities • Diminished lipid peroxidation	Abbas (2012)
C. frutescens	0, 3 and 7 μM Na_2SeO_3	HM, 0.25–0.5 mM $CdCl_2$	• Improved growth • Improved photosynthetic pigments • Decreased Pro • Enhanced CAT activity	Shekari et al. (2016)
B. napus	50 and 100 μM Se (Na_2SeO_4), 24 h	HM. 0.5 and 1.0 mM $CdCl_2$, 48 h	• Increased the AsA and GSH contents, the GSH/GSSG ratio • Increased activities of APX, MDHAR, DHAR, GR, GPX, and CAT • Reduced the MDA and H_2O_2 levels	Hasanuzzaman et al. (2012b)
B. napus	2 μM Na_2SeO_4, 14 days	HM, 400 and 600 μM, $CdCl_2$, 14 days	• Reduced oxidative stress by modulating SOD, CAT, APX, GPX activities • Prevented Cd-induced alteration of DNA methylation pattern	Filek et al. (2008)

(continued)

Table 10.2 (continued)

Plant species	Trace elements	Stress	Beneficial effects	References
Pteris vittata	5, 10 µM of Na_2SeO_4, 5 and 10 days	HM, 150 or 300 µM of Na_2HAsO_4, 10 days	• Improved antioxidant system including thiol and GSH levels • Reduced As uptake	Srivastava et al. (2009)
B. oleracea	1 mg L^{-1} Na_2SeO_3, 10 and 40 days	HM, 1 mg L^{-1} $CdCl_2$, 40 days	• Increased chl content • Improved α-tocopherol level and reduced oxidative damage	Pedrero et al. (2008)
Lolium perenne	1.0, 1.5, 2.0, 5.0 and 10 µM Na_2SeO_3, 20 days	HM, 0.2 mM $AlCl_3$, 20 days	• Improved POD activity • Reduced $O_2^{\bullet-}$ and lipid peroxidation	Cartes et al. (2010)
T. aestivum	1.0 and 2.0 mg Se kg^{-1}, 8 h	UV-B, 40 W, 305 nm, 8 h	• Increased root weight and root activity • Increased flavonoids and Pro content • Increased activities of POD and SOD • Reduced MDA and $O_2^{\bullet-}$	Yao et al. (2009)
Euglena gracilis	10^{-7}, 10^{-8}, 10^{-9} and 10^{-10} M, $Na_2SeO_3 \cdot 5H_2O$, 40 min	UV-A, 320–400 nm, 40 min	• Improved light-enhanced dark respiration and photosynthesis	Ekelund and Danilov (2001)

deficiency and excess Cu conditions (Yruela 2005). Copper is found to be actively involved in many antioxidant enzymes in plants. Growth, protein content, and antioxidant enzymes' activities showed differential responses under different concentrations of copper (0–800 µM) as reported by Gao et al. (2008). Higher activities of enzymes in *Jatropha curcas* seedlings were observed at the concentration of 200–400 µM. However, it was also dependent of plant organs. Azooz et al. (2012) observed the effect of Cu in wheat and found that 2 mM Cu showed optimum growth and biochemical parameters, while no changes were observed up to 10 mM Cu, and thereafter, the growth and biochemical parameters were significantly reduced. The activities of antioxidant enzymes such as CAT, POD, APX, and SOD were increased in dose-dependent manners. This effect of Cu in plants was associated with the biosynthesis of free amino acids and Pro (Azooz et al. 2012).

10.6.2 Zinc

Since 1932, Zinc has been considered as a vital micronutrient for plants because its participation as a functional component of around 200 enzymes and transcription factor involved in biomolecule synthesis and metabolism of nucleic acid and lipid. Furthermore, Zn plays role in biomass production, chl formation, pollen function, and fertilization (Ebrahimian and Bybordi 2011; Hafeez et al. 2013). Zn (at low concentration 1–2 μM) increases plant growth, chl content, and crude protein (Samreen et al. 2013). Role of Zn in conferring drought stress tolerance maintaining water use efficiency was described by Waraich and his group (Waraich et al. 2011a, b). They proposed that Zn can enhance the auxin level directly or indirectly by increasing tryptophan which is a precursor of auxin. Then auxin increased the root growth under drought condition. In addition, Zn decreases the activity of membrane-bound NADPH oxidase; for this reason, ROS generation decline and SOD, CAT, and POD activities increase to protect cell from oxidative damage under drought stress. Cd-induced damage can be restored by using Zn. Wu and Zhang (2002) reported Cd-induced reduction in root and shoot biomass, micronutrient imbalance (Cu, Fe, and Zn), and higher amount of Cd uptake reduced by the application of 300 μmol L^{-1} Zn. Exogenous Zn prevented the Cd uptake by making block, maintained micronutrient (Cu, Fe, and Zn), reduced MDA, and, at the same time, increased antioxidant enzyme activity to protect barley plant from Cd toxicity. Supplemental Zn can reduce salinity-induced oxidative stress by reducing MDA, H_2O_2, and lipoxygenase activities as well as increasing APX and CAT activity in pistachio seedling (Tavallali et al. 2010). Application of Zn increased fresh and dry weight and Pro content and enhanced the activities of CAT, SOD, and GST under salt stress in sunflower leaves (Ebrahimian and Bybordi 2011). Role of Zn in abiotic stress tolerance is still ambiguous. Further study is required to find out mechanism of Zn-induced abiotic stress tolerance and elucidate nature of interaction among Zn and other nutrient elements.

10.6.3 Nickel

Although the biological functions of Ni in plants have been reported since long time, its essentiality has been established recently due to its role as an activator of the enzyme urease (Fabiano et al. 2015). However, its role as protectants of plant stress is rarely available rather than its toxic effects. Recent studies have shown that Ni may activate *OsGLY11.2* (an isoform of glyoxalase I), which is the first line of enzymes in the degradation of cytotoxic methylglyoxal (MG) (Mustafiz et al. 2014), a cytotoxic compound which is produced in high concentration under stress. This MG is detoxified via glyoxalase system where both Gly I and Gly II enzymes are involved. Importance of Ni for the activity of Gly I not only suggest its role in MG detoxification but also the redox state of GSH which is a strong antioxidant and vital player in metal tolerance. Fabiano et al. (2015) studied the role of Ni in the relationship between the MG cycle and GSH homeostasis and stated that Ni may have a key participation in plant antioxidant metabolism, especially in stressful situations (Fabiano et al. 2015). However, further study is necessary to elucidate the actual functions of Ni in conferring stress tolerance to plants.

10.6.4 Boron

Though the physiological role of B in plant is still unclear, it is evident that both the deficiency and toxicity of B resulted in many anatomical, biochemical, and physiological changes in plants (Herrera-Rodríguez et al. 2010). The deficiency of B in plant affects growth and reduces yield, whereas sufficient supply results in better growth and good yield (Shabaan 2010). As an essential element, B is required for many essential functions of plant such as maintaining cell structures and functions as well as cell division, sugar transport, hormone development, respiration, carbohydrate metabolism, membrane transport, and transportation and metabolism of other essential plant nutrients (Shabaan 2010, Herrera-Rodríguez et al. 2010). Boron can also play role in fruit and seed development by increasing fertility, pollen tube growth, and carbohydrate utilization (Blevins and Lukaszewski 1994). Therefore, deficiency of B causes many physiological and biochemical changes in plant that affect plant growth and yield (Shabaan 2010). It is also revealed that exogenous B can develop stress tolerance by regulating physiological and biochemical attributes under environmental stress condition. Foliar application of B improves growth and yield of wheat by increasing chl and Car content and decreasing H_2O_2 and Pro content under drought stress condition (Abdel-Motagally and El-Zohri 2016). Moeinian et al. (2011) also showed that foliar application of B improve growth, yield, and grain quality of *T. aestivum* under drought stress condition by improving leaf area index (LAI), crop growth rate (CGR), and net assimilation rate (NAR). Foliar application of B alleviates salinity and improves growth and yield attributes in maize seedlings under salt stress by regulating phenols, proline, amino acids, and soluble sugar (Salim 2014). Zhou et al. (2015) reported that gene related to ROS and aldehyde detoxification and metabolism, cell transport, Ca signaling, and hormone and gene regulation play role in B-induced alleviation of aluminum toxicity in *Citrus grandis* seedlings.

10.6.5 Manganese

As an essential trace element, manganese (Mn) is associated with various plant metabolic processes. It plays an important role in plant photosynthesis, respiration, and hormone activation. It also takes part in synthesis of protein, lipid, fatty acids, amino acids, ATP, flavonoids, etc. (Lidon et al. 2004; Millaleo et al. 2010). Usually Mn presents in soil as free Mn^{2+} which is only available form for plant and readily taken up by plant via an active transport system in epidermal root cells. Deficiency of Mn is dangerous for plant, because it weakens structural resistance against pathogen and decreased tolerance ability toward abiotic stresses such as heat and drought stress. In addition, Mn deficiency also affects the water-splitting system of photosystem II (PS II) that provides electron directly for photosynthesis which also makes plant vulnerable toward stress (Gherardi and Rengel 2003; Millaleo et al. 2010). On the other hand, the presence of excess Mn in plant root zone also extremely toxic to plant. Higher accumulation of Mn by plant alters various physiological and metabolic processes which causes chlorosis, necrosis, oxidative stress, and growth and yield reduction (Ducic and Polle 2005; Millaleo et al. 2010; Arya and Roy 2011). Considering the beneficial role of lower amount and toxic effect of excess amount, Mn plays dual role in plant system: essential micronutrient and toxic element, respectively (Ducic and Polle 2005; Millaleo et al. 2010).

However, among the beneficial roles that we discussed, Mn also plays role directly against various abiotic stresses. Being a divalent cation, Mn can compete with other divalent toxic ion and reduced their uptaken and transportation within plant as they are uptaken by active transporter and have some common transporter during uptake and transportation (Hirschi et al. 2000; Pittman 2005). In addition, Mn also acts as cofactor in Mn-CAT and Mn-SOD enzymes that participates in plant antioxidant defense system. Although it is not clear but assumed that Mn acts as $O_2^{\cdot -}$ and H_2O_2 scavenger (Ducic and Polle 2005). Moreover, many studies revealed that supplemental Mn plays positive role in conferring stress tolerance under various abiotic stress conditions (Table 10.2). Supplementation of Mn in Cd-treated plant improves growth and chl and Car contents and decrease lipid peroxidation by reducing Cd uptake and enhancing antioxidant defense system (Pal'ove-Balang et al. 2006; Peng et al. 2008; Sebastian and Prasad 2015). Exogenous application of Mn in barley seedlings confer salt stress tolerance and improve growth by increasing net assimilation and photosynthetic rate under salt stress condition (Cramer and Nowak 1992; Pandya et al. 2004). Upadhyaya et al. (2012) reported that Mn plays positive role on post-drought stress recovery in tea by influencing growth and antioxidative response. To observe the protective effect of Mn under salt stress condition, we have grown 12-day-old *O. sativa* seedlings under 150 mM NaCl for 3 and 6 days under controlled environment. Salt stress resulted in marked increase in Na^+, MDA, H_2O_2, $O_2^{\bullet -}$, and Pro and MG content which in turns exhibited chlorosis and growth inhibition in time-dependent manner (Rahman et al. 2016). On the other hand, Mn supplementation (0.5 mM MnSO4) reduced oxidative stress by lowering the levels of MDA and H_2O_2 and enhancing the activities MDHAR, DHAR, SOD, CAT, Gly I, and Gly II and improving the contents of nonenzymatic antioxidants. Exogenous Mn also maintains low Na^+ and high K^+ content and thus maintained ion homeostasis.

10.6.6 Silicon

Although it is not considered as essential for plant function, in rice, Si showed some essential functions, and it is absorbed from soil in amounts that are even higher than those of the essential macronutrients (Datnoff et al. 2001). There are plenty of evidences on the role of Si in plant stress tolerance (Hasanuzzaman et al. 2014b). Beneficial effects of exogenous Si in enhancing abiotic stress resistance are reported in many plant studies (Table 10.2). The protective effect of Si under abiotic stress are mainly due to the deposition of Si as $SiO_2.nH_2O$ in leaves and stems of plants and partly by the interaction between $Si(OH)_4$ and other elements such as Al. It is also suggested that the function of Si in plants might involve mechanical defense rather than physiological changes (Fig. 10.4; Ma and Yamaji 2008; Hasanuzzaman et al. 2014b).

Hydroponically supplemented Si (1.8 mM K_2SiO_3) significantly increased growth and alleviated salinity stress (50 mM NaCl) in *C. annuum* which was due the enhancement of antioxidant defense, improvement of photosynthesis, and maintenance of the nutrient balance (Manivannan et al. 2016). For example, electrolyte leakage potential in salt stress treatment by 38% upon exposure illustrated the NaCl-induced cell membrane damage, which, in turn, was reduced by 33% upon Si supplementation. Similarly, the addition of Si mitigated the oxidative damage by decreasing the MDA content by 29% and H_2O_2 content by 26% which efficiently minimized the oxidative burst. While investigating the beneficial role of Si in salt stressed (10 dS/m) *Anethum graveolens*, Shekari et al. (2015) observed that exogenous Si (1.5 mM) could be able to improve the salt-induced inhibition of growth and

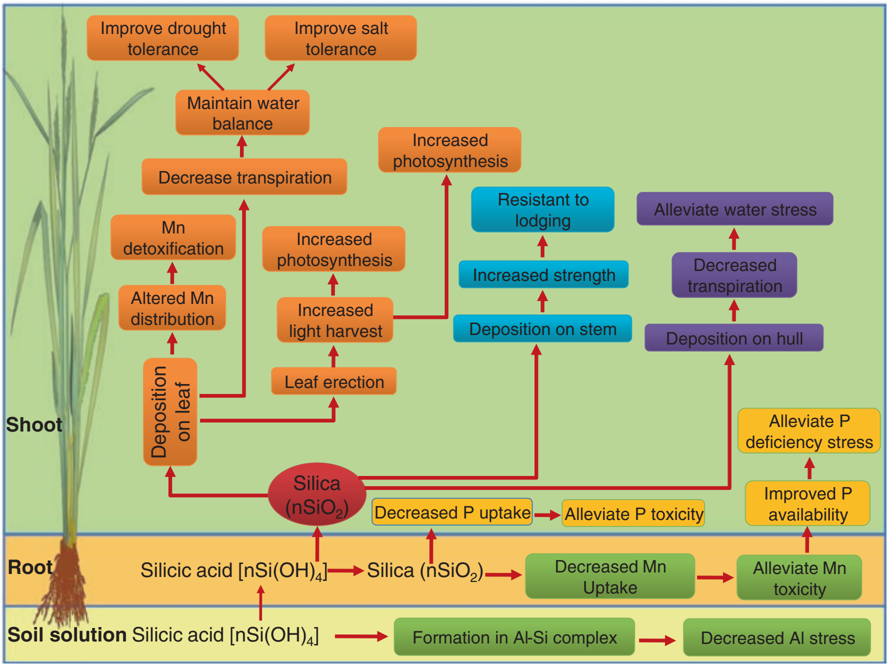


Fig. 10.4 Silicon-induced abiotic stress tolerance in plants (Source: Hasanuzzaman et al. 2014b, with permission from Elsevier)

Na/K ratio. Silicon also reduced lipid peroxidation which was associated with enhanced activities of antioxidant enzymes. Mateos-Naranjo et al. (2013) observed that Si could ameliorate nutrient imbalances in salt affected *Spartina densiflora*. The K^+/Na^+ ratio of leaves of *Spartina densiflora* was greater in Si-treated plants, and these plants also had higher levels of essential nutrients (Si, Al, Cu, Fe, K, and P) in their tissues (Mateos-Naranjo et al. 2013). In *B. napus*, Si (2 and 4 mM) was found to be effective in enhancing antioxidative enzyme activities and photosynthesis (Bybordi 2012). Protective role of Si in drought stress tolerance was reported by many authors. These effects were mainly due to the maintenance of water balance, cellular integrity, and antioxidant defense. However, little information is available on its role in water uptake and in less Si-accumulating plants. Silicon also provided better protection under alkali stress (25–75 mM Na_2CO_3). After 25 days of stress growth parameters, leaf RWC, and the contents of photosynthetic pigments, soluble sugars, total phenols and potassium ion (K^+), as well as potassium/sodium ion (K^+/Na^+) ratio were decreased, while the contents of soluble proteins, total free amino acids, proline, Na^+ and MDA, as well as the activities of SOD, CAT, and POD were increased. On the other hand, seed priming with 1.5 mM $Na_2O_3Si.5H_2O$ improved growth of stressed plants, which was accompanied by the enhancement in leaf RWC and levels of photosynthetic pigments, soluble sugars, soluble proteins, total free amino acids and K^+, as well as activities of SOD, CAT, and POD enzymes. Furthermore, Si supplement resulted in a decrease in the contents of Pro, MDA, and Na^+, which together with enhanced K^+ level led to a favorable adjustment of K^+/Na^+ ratio, in stressed plants relative to plants treated with alkaline stress alone. In a recent report, Shi et al. (2016) found increased water uptake and less oxidative damage in *S. lycopersicum* under drought stress (10% PEG) when Si (2.5 mM) was applied. Silicon addition significantly recovered the growth and photosynthetic inhibition and improved water status in plants compared to water stress alone. There was a marked increase in ROS accumulation under water stress, while added Si ameliorated these by enhancing the activities of SOD and CAT and maintaining the AsA and GSH levels higher (Shi et al. 2016). Mauad et al. (2016) reported that Si-induced drought stress tolerance was developed due to increased Pro synthesis and peroxidase (POX) activity.

In *Z. mays*, foliarly applied Si (10 mM K_2SiO_3 metasilicate) could enhance chilling tolerance to low-temperature (3 ± 1 °C) stress (Habibi 2016). Maize plants grown under low temperature resulted in marked reduction of plant growth and RWC, increased the production of ROS, and depleted the photosynthetic parameters. However, Si supplemented plants showed revisable effect, i.e., decrease in lipid peroxidation and increase in maximum quantum yield of PS II (Fv/Fm) and photosynthetic pigments. Silicon supplementation also maintained the AsA and GSH pool (Habibi 2016). Several studies indicated that Si is also effective in mitigating metal toxicity in plants. Hydroponically grown rice plants exposed to 10 μM $CdCl_2$ showed inhibition of plant growth and photosynthesis as well as disruption of ion homeostasis and antioxidant defense (Farooq et al. 2016). However, when the plants were supplemented with 0.6 mM $Si(OH)_4$, it reversed the effects of Cd by improving plant growth, photosynthesis, nutrient homeostasis, and enhancement of antioxidant defense system, especially AsA-GSH cycle, and thus readjusting cell redox homeostasis (Farooq et al. 2016). In *S. nigrum*, Si-induced Cd stress tolerance was associated with the activation of antioxidant defense and reduction of Cd uptake as reported by Liu et al. (2013). They observed that Cd markedly enhanced the production of ROS and showed higher electrolyte leakage and accumulated higher amount of Cd in shoot and root. In contrary, Si reduced H_2O_2 accumulation and prevented cell death and the electrolyte leakage and H_2O_2 concentration in functional leaves. Si supplementation also enhanced the activities of SOD, CAT POD, and APX (Liu et al. 2013).

10.6.7 Selenium

After the intense research of past few decades, the beneficial roles of Se in plants have been observed, but the question is still unresolved whether Se is an essential micronutrient for plants (Terry et al. 2000). However, it is still recognized as an essential micronutrient (Hasanuzzaman et al. 2014b). In many plant species, Se exerts a positive effect on plant growth, physiology, and productivity under abiotic stress (Hasanuzzaman et al. 2010, 2011b, 2012b, 2014a, b; Table 10.2). One of the roles of Se in exerting beneficial effects on the stress tolerance is the enhancement of the antioxidant capacity (Hasanuzzaman et al. 2014a, b).

Several research results have shown that Se at low concentration provided protection to different plant species against salt stress. Selenium-induced growth promotion and improvement of photosynthesis and antioxidant defense system in salt-treated tomato plants were reported by Diao et al. (2014). Under salt stress (100 mM NaCl), plant growth and photosynthetic attributes were inhibited while Se supplementation (50 μM Na_2SeO_3) reversed the effects. Se treatment also limited the ROS generation which was mainly due to the enhanced activities of SOD, GR, DHAR, MDHAR, and GPX and the redox pool of AsA and GSH (Diao et al. 2014). In pot culture Se (5–10 μM) supplemented *V. unguiculata* showed enhanced tolerance to salt stress (50 mM NaCl) through the highest values of photosynthetic pigments, proline, phenylalanine ammonia lyase (PAL), and total soluble sugar as well as growth and yield attributes (Manaf 2016). In a recent study, we found that exogenous Se (5-10 μM) could alleviate salt (25–50 mM NaCl)-induced damages by improving the integrity of cell membranes and by increasing leaf RWC, and photosynthetic pigments under stress conditions and subsequently increasing plant biomass and yield (Mozafariyan et al. 2016). Under high salt concentration (50 mM NaCl) 10 μM Se performed well than other dose.

Kong et al. (2005) reported that low concentrations (1–5 μM) of Se stimulated growth and enhanced antioxidant enzyme (SOD and POD) activities in leaves of sorrel (*R. patientia* × *R. tianshanicus*) seedlings under salt stress. In contrast, at higher concentrations (10–30 μM), Se showed fewer beneficial effects. In *C. sativus* leaves, Se treatments (5–10 μM) increased the growth, synthesis of photosynthetic pigments, and Pro levels under salt stress (Hawrylak-Nowak 2009). In our recent study, we observed beneficial effects of exogenous Se (25 μM Na_2SeO_4) in salt (100 and 200 mM NaCl)-stressed *B. napus* seedlings (Hasanuzzaman et al. 2011a, b). Selenium treatment increased the components of AsA-GSH cycle and other antioxidant enzymes and maintained the AsA and GSH pool which reduced levels of H_2O_2 and MDA when compared to plants exposed to salt stress alone (Hasanuzzaman et al. 2011a, b). So far the confirmation about which form of Se is more effective is yet to be elucidated. In a recent study Hawrylak-Nowak (2015) reported that Se application, especially in the form of selenite, could upregulate the antioxidant defense in salt-treated lettuce. It was also found that the root growth and increase in photosynthetic pigment were increased upon Se supplementation.

Several plant studies that focused on the protective effects of Se under drought stress indicated that the effects of Se are due to its ability to regulate the water status of plants under water-deficit condition. In wheat, Se supplementation improved dry matter and grain yield under both well watered and a drought condition which was mainly due to enhancement of photosynthesis rate, protection of leaf photochemical events, accumulation of organic osmolytes, and improvement of water use efficiency. Selenium was also able to increase root length and diameter which made the plant able to uptake more water and maintaining higher water content in leaves (Hajiboland et al. 2016). Nawaz et al. (2014) reported that the growth and biomass of wheat seedlings increased under drought due to Se fertigation. Se supplemented seedlings showed higher stress tolerance index and biomass with 7.06 μM Se. Kuznetsov et al. (2003) reported that the addition of 0.1 or 0.25 mM Se caused a 2–6% increase in leaf water content, thereby increasing the drought resistance. The Se-induced improvement in leaf tissue water status was accompanied by a sharp (two to fourfold) inhibition of stress-induced accumulation of Pro and a significant inhibition of POX activity (Kuznetsov et al. 2003). Wang et al. (2011) examined the effect of Se (5 μM Na_2SeO_4) on the AsA-GSH cycle in *Trifolium repens* seedlings subjected to drought. They observed that Se application decreased the lipid peroxidation and H_2O_2 by maintaining the higher AsA and GSH pool higher. Selenium supplementation significantly increased the activities of MDHAR, DHAR, and GR. Among the enzymes, GR showed the highest increase in activity compared to DHAR and MDHAR. In our laboratory, we studied the beneficial role of Se pretreatment (25 μM Na_2SeO_4, 48 h) in *B. napus* seedlings under drought stress (10 and 20% PEG-6000) (Hasanuzzaman and Fujita 2011). Drought-stressed seedlings showed increases in GSH and GSSG content; however, the AsA content increased only under moderate stress (Table 8). The MDHAR and GR activities increased only under moderate stress (10% PEG). The activities of DHAR, GST, and GPX significantly increased at all levels of drought, while CAT activity decreased. Drought stress resulted in a marked increase in the levels of H_2O_2 and MDA. In contrast, Se-pretreated seedlings exposed to drought stress showed a rise in AsA and GSH content and upregulated activities of CAT, APX, DHAR, MDHAR, GR, GST, and GPX when compared with the drought-stressed seedlings without Se. In turn, the Se-treated seedlings showed a considerable decrease in the levels of H_2O_2 and MDA and considerable alleviation of oxidative stress (Hasanuzzaman and Fujita 2011). Very recently, Nawaz et al. (2013) found beneficial role of Se priming in conferring drought stress tolerance. In their experiment, seeds of *T. aestivum* were soaked in distilled water or Na_2SeO_4 solutions (25, 50, 75, and 100 μM) for 30 or 60 min, followed by re-drying and subsequent sowing. Priming with Se significantly increased root length, stress tolerance index, and total biomass of germinated seedlings. Yildiztugay et al. (2016) observed that exogenous Se could upregulate the AsA-GSH cycle in heat-exposed *Z. mays* plants and minimized the overproduction of ROS which in turns protected the plants from oxidative stress induced by drought (25% PEG).

Recent studies also indicated the protective role of Se under HT stress. Yildiztugay et al. (2016) observed that exogenous Se could upregulate the AsA-GSH cycle in heat-exposed *Z. mays* plants and minimized the overproduction of ROS which in turns protected the plants from oxidative stress induced by HT (24–44 °C). Exogenously applied Se also found to be effective under HT stress in spring wheat under field condition. Heat stress (38 ± 2 °C) significantly depleted the antioxidative potential, affected growth, photosynthetic pigments, and grain yield of wheat which were satisfactorily reversed by Se supplementation which helped the wheat plants to increase fertility and hence avoid reduction of grain yield under HT stress (Iqbal et al. 2015). Djanaguiraman et al. (2010) reported that beneficial effect of foliarly applied Se (75 mg L^{-1}) could enhance photosynthesis, membrane integrity, and antioxidant defense which improved the yield components and grain yield of *S. bicolor* plants grown under HT stress (40/30 °C). Se application increased photosynthetic rate and stomatal conductance in HT-stressed plants by 13.2 and 12.4%, respectively, compared to non-supplemented plants under stress, while the $O_2^{\bullet-}$, H_2O_2 and MDA content decreased by 11.5, 35.4 and 28.4%, respectively. Recently, we found that Se could minimize HT-induced damages to *B. napus* seedlings by enhancing antioxidant defense and glyoxalase systems (Hasanuzzaman et al. 2014b). Heat (38 °C, 24 and 48 h)-exposed seedlings exhibited marked decrease in the chl content and increased RWC, MDA, H_2O_2, Pro, and MG contents in time-dependent manners. Selenium supplemented HT-treated seedlings recovered these damages which were evident with decrease level of MDA, H_2O_2, and MG which was correlated with enhanced ecaivities of CAT, GPX, MDHAR, DHAR, GR, Gly I, and Gly II as well as higher redox balance of AsA and GSH (Hasanuzzaman et al. 2014b). Protective role of Se under LT stress has been reported in few plant studies, but the effect was mostly dose dependent. According to Djanaguiraman et al. (2005), Se was able to increase the tolerance of *G. max* plants to LT stress by promoting antioxidant capacity, and it improved growth and developmental processes of that plant under LT. Recently, Abbas (2012) found that SeO_4^{2-} at low concentrations (3 and 6 mg L^{-1}) enhanced growth, levels of chl, anthocyanin, sugar, Pro, and AsA, and enzymatic activities in *S. bicolor* seedlings subjected to LT stress. However, high levels of SeO_4^{2-} (12 mg L^{-1}) resulted in toxic effects. Low levels of SeO_4^{2-} (3 and 6 mg L^{-1}) also diminished lipid peroxidation by enhancing the activities of APX and GPX.

Selenium has been documented to reduce metal toxicity in several research studies. The modes of action were varied and are still unclear; however, some suggested reasons included improvement of the antioxidant defense system, reduction of metal uptake, formation of nontoxic Se-metal complexes, and phytochelatin activity (Vorobets and Mykiyevich 2000; Sun et al. 2010). Moreover, Se is effective at sustaining physiological activities, growth, and developmental processes even in HM toxic environments (Pedrero et al. 2008; Cartes et al. 2010). A study on peeper showed that Se supplementation diminished Cd toxicity on photosynthesis pigment (Shekari et al. 2016). The application of Selenium at 7 μM significantly increased leaf area in the plants grower at 0.25 mM Cd. The application Se at 3 μM with 0.25 mM Cd and Se 3 and 7 μM with 0.5 mM Cd increased the activity of CAT. Selenium 7 μM decreased Pro content of pepper leaves exposed to Cd 0.5 mM (30%). Selenium significantly enhanced antioxidant activity of leaves which was diminished by Cd toxicity. In general, Se has beneficial effect on plant growth and antioxidant enzymes of pepper under Cd stress and nonstress conditions (Shekari et al. 2016). In *B. oleracea*, Cd phytotoxicity resulted in elevated MDA level and decreased photosynthetic pigment and tocopherol concentrations, but Se treatment effectively alleviated these adverse effects (Pedrero et al. 2008). In *B. napus*, Se (2 μM) conferred tolerance to Cd (400 and 600 μM) stress by reducing lipid unsaturation and peroxidation, modulating the activity of antioxidative enzymes (SOD, CAT, APX, GPX), and preventing Cd-induced changes in the DNA methylation pattern (Filek et al. 2008). Sun et al. (2010) showed that enhanced Cd tolerance by Se might be due to removal of Cd from metabolically active cellular sites, induction of Se to scavenge the Cd-induced ROS generated, and the regulation phytochelatin synthesis associated enzymes induced by of Se. In our recent study, we observed that rapeseed seedlings grown under Cd stress (0.5 and 1.0 mM $CdCl_2$) showed substantial increases in MDA and H_2O_2 levels (Hasanuzzaman et al. 2012b). The AsA content of the seedlings decreased significantly upon exposure to Cd stress. The amount of GSH increased only at 0.5 mM $CdCl_2$, while GSSG increased at any level Cd with concomitant decreases in the GSH/GSSG ratio. The activities of antioxidant enzymes also reduced under Cd stress. Importantly, Se-pretreated seedlings exposed to Cd showed increases in the AsA and GSH contents, GSH/GSSG ratio, and the activities of APX, MDHAR, DHAR, GR, GPX, and CAT. However, in most of the cases, pretreatment with 50 μM Se showed better results compared to 100 μM Se. These results indicated that the exogenous application of Se at low concentration increased the tolerance of the plants to Cd-induced oxidative damage by enhancing their antioxidant defenses (Hasanuzzaman et al. 2012b).

Selenium improves plant growth and survival under UV radiation, as reported in several studies. Se (0.01 and 0.05 mg kg^{-1} soil) improved the antioxidative capacity, protected chloroplast enzymes, and increased shoot yield in *Lactuca sativa* under combined UV-B and UV-C stress (Pennanen et al. 2002). Significant increases in the activities of POD and SOD, together with reduced MDA and $O_2^{\bullet-}$levels, were documented in *T. aestivum* under UV-B radiation. Selenium also increased root activity, flavonoid, and Pro contents in this plant (Yao et al. 2010). Recently, we completed a pot experiment with three rice varieties, viz., BRRI dhan45, BRRI dhan47, and Nipponbare grown under different concentration of salt water (50–150 mM). Salt stresses reduced the plant height and tillers $hill^{-1}$, leaf relative water con-

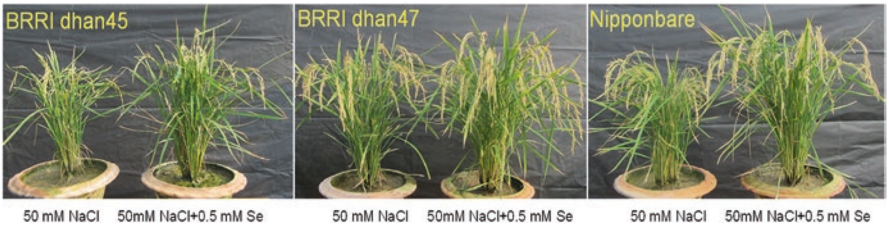


Fig. 10.5 Effect of Se supplementation in mitigating adverse effects of salt stress in different rice cultivars. Plants were subjected to 50 mM NaCl throughout its life cycles with or without 0.5 mM Na_2SeO_3

tent, and chl content in dose-dependent manner. Salt stress also reduced the effective tillers hill^{-1}, number of filled grains panicle^{-1}, 1000-grain weight, grain yield, and straw yield. However, when the plants were supplemented with 0.5 mM Se (sodium selenite, Na_2SeO_3), these observed parameters were significantly increased compared to salt treatment alone. Importantly, the beneficial effect of Se on salt stress tolerance was prominent up to 100 mM NaCl, while it could not be more beneficial above this level of salt concentration (Naim 2015). The response of rice plant to Se and salt stress greatly varied in different cultivars (Fig. 10.5).

10.7 Molecular Approaches to Manipulate the Genes Associated with Trace Elements Actions in Plants

Plant cannot synthesize inorganic molecule including macronutrient, micronutrient, and heavy metals. But plant can uptake inorganic molecule from growing medium using root. To get entry into root or to be translocated, metal ions are needed to cross both cellular and organellar membranes. These membranes contain different transporter proteins which show specificity to particular inorganic elements (Guerinot 2000). For example, IRT1 is a transporter protein which shows specificity to Fe, but Mn and Zn can also be transported using this transporter. Similarly ZIP1, ZIP2, and ZIP3 act as Zn transporter in plant and *AtECA1* for Ca^{2+} and Mn^{2+}, *AtNramp3* for Mn^{2+}, Fe^{2+} and Cd^{2+} in Fe-deficiency conditions, *AtOPT3* for possible transport of Cu^{2+} and Fe^{2+} and Mn^{2+}, and so on (Millaleo et al. 2010). Many genes already identified those encode these transporter proteins. Expression of transporter gene depends on the presence or absence of a particular ion. Regulation of genes at transcriptional and posttranscriptional level controls metal uptake as excessive accumulation metal ions cause toxicity to plants. For instance, sensing the intracellular Zn level, Zn-responsive transcriptional activator protein ZAP1 induces gene expression to uptake Zn. On the other hand, Zn uptake reduced by endocytosis of ZRT1 transporter protein (Guerinot 2000).

Abiotic stress limits ion uptake in plants. The roles of trace element in different types of abiotic stresses are well discussed in previous sections. But with the blessing of modern science, it is possible to manipulate the genes related to trace element uptake. Increasing trace element content in plant by overexpression of gene may enhance tolerance against drought, salinity, and heavy metal toxicity (Table 10.3). Very limited literatures are found in this research area. Li et al. (2011) found that overexpressed Na^+/H^+ antiporter (*AtNHX5*) gene induced extreme dehydration tolerance in paper mulberry. The *AtNHX5*-overexpressing plants survived under drought and salinity, whereas the wild-type (WT) plants could not survive. Under salt stress, *AtNHX5*-overexpressed plant contained higher amounts of Na^+ and K^+ in leaves compared to WT. Higher leaf water content and leaf chl contents, Pro and soluble sugars, and less membrane damage were observed in transgenic plants than the WT plants under both drought and saline conditions. They suggested the possibility of *AtNHX5* gene in improving the tolerance against abiotic stresses in paper mulberry plants. In another study, Sasaki et al. (2016) reported that overexpression of *OsHMA3* showed Cd toxicity tolerance. *OsHMA3*-overexpressed line alleviated the Cd-inhibited growth. Higher amount of Cd found in the roots of *OsHMA3*-overexpressed line than shoots of wild type and vector control line. This result suggests the role of *OsHMA3* in enhancing vacuolar sequestration of Cd in the roots. Furthermore, the *OsHMA3*-overexpressed line constitutively upregulates five transporter genes belonging to the ZIP family. They finally proposed that overexpression of *OsHMA3* is an efficient way to reduce Cd accumulation in the grain and to enhance Cd tolerance in rice.

Table 10.3 Overexpressed transporters that enhance abiotic stress tolerance

Transporter gene	Effects	References
NcZNT1	Overexpression of *NcZNT1* conferred tolerance against high Cd and Zn in *A. thaliana*	Lin et al. (2016)
ZTP29	*Arabidopsis* zinc transporter *ZTP29* was involved in the response to salt stress, may be due to Zn-induced upregulation of the UPR pathway	Wang et al. (2010)
NIP5;1	Enhanced expression of *NIP5;1* in *A. thaliana* promoted root growth under B deficiency condition	Kato et al. (2009)
AtNHX1	Overexpression of this gene enhanced salinity stress tolerance in wheat by reducing Na^+	Xue et al. (2004)
OsNHX1	Overexpressed *OsNHX1* increased K^+ under salinity thus contributed to salt stress tolerance and promoted growth of maize	Chen et al. (2007)
NtCBP4	This gene was responsible for Ni toxicity by reducing Ni^{2+} uptake in transgenic tobacco plant	Arazi et al. (1999)
CAX2	Overexpression of this gene increased Cd and Mn toxicity though transgenic tobacco plant accumulated more Cd and Mn	Hirschi et al. (2000)
CsMTP8	High or low amount of Mn-induced upregulation or downregulation improved Mn homeostasis in cucumber	Migocka et al. (2014)

10.8 Conclusions and Outlooks

The trace elements are not critical for all plants but may improve plant growth and yield through their different beneficial influences on plants' physiological and morphological mechanisms. Essential trace elements or micronutrients are elements necessary for maintaining the life processes in plants. The continous hammering on soil for producing more foods without allowing time for natural replenishment of the nutrients uptaken by plants from the same piece of land has led to evolution of newer elements essential for plants. Trace elements present at very low concentrations in agroecosystems are essential to plant growth and development. Both deficiency and toxicity of trace elements occur in agroecosystems. However, the range of essential to lethal for these elements is rather thin. Application of trace elements in fertilizers is effective in correcting micronutrient deficiencies for crop production, whereas, though costlier, remediation of soils contaminated with metals through phytoremediation appears promising as a cost-effective approach. Stressed plant suffering from due by far but not limited to climatic change/aberrations, seasonal rotations, or geographical positions around the globe are galore (Hasanuzzaman et al. 2014b). Plants also develop physiological and morphological mechanisms for adaptations with the stressful conditions. On reflection of the research works have been conducted so far, it can be said that participation of trace elements in mechanisms of stress tolerance in plants is very vital (Hasanuzzaman et al. 2011b). To be more specific, under adverse environmental conditions, supplementing trace elements have mostly beneficial effects in plant survival, vegetative growth, and reproductive growth and productivity (yield), unless they are in toxic concentration in soil-plant systems. As for example, 50 mg B L^{-1} foliar spray at booting and anthesis stage of *Triticum aestivum* reduces drought stress effects on plants through increasing chl and Car and decreasing H_2O_2 and Pro content (Abdel-Motagally and El-Zohri 2016). Abiotic stress-induced oxidative stress is another phenomena that plants experienced under different stress conditions such as waterlogging, drought, salinity, heat, ozone, UV-B radiation, redox-active metals, etc. but trace elements can mitigate through different ways, for example, by reducing the production of ROS and other radicals. Besides these, the actions of trace elements on a wide range of crops (*Euglena gracilis* to *Oryza sativa*) have been tested in terms of tolerance or avoidance of abiotic stresses, and the results were positive to a great extent.

Trace elements are indispensable part for either physiological, biochemical or molecular approach of stress tolerant mechanism development in plants. To exemplify, *Arabidopsis* zinc transporter *ZTP29* was involved in the response to salt stress through Zn-induced upregulation of the unfolded protein response (UPR) pathway, and overexpression of *AtNHX1* gene reduced Na^+ content in plant and enhanced salinity stress tolerance in wheat. The reviewed research results on role of trace elements on abiotic stress tolerance in plants predict that trace elements are only trace for their presence, but they are huge for their actions and overlooking them as trace elements will results in failure of developing tolerance in plants to abiotic stresses.

However, thorough actions of trace elements on abiotic stress avoidance, tolerance, or resistance mechanisms by plants are still poorly understood for drawing out a full panorama. Foolproof researches focusing on the equilibrium of trace elements in an agroecosystem and elaboration of soil biochemical and molecular approaches that can be used to diagnose trace elements responsible for stress control and to use for future use are urgently needed. Besides these, most of the experiments conducted around the world on actions of beneficial trace elements on plant tolerance of abiotic stresses are confined mostly to laboratory conditions and short-term studies only. Field performances of the biochemical, molecular approaches along with agronomic management practices are also needed to strengthen the science of plants tolerance to abiotic stresses.

Acknowledgments At the very first the authors wish to thank Taufika Islam Anee, Tasnim Farha Bhuiyan, and Mazhar Ul Alam, Laboratory of Plant Stress Responses and Faculty of Agriculture, Kagawa University, Japan, for their critical readings and suggestions in improving the manuscript. We are also highly thankful to Mr. Md. Rumainul Islam, Environmental Engineering Program, Chongqing University, China, for providing us several supporting articles. The first author acknowledges Japan Society for the Promotion of Science (JSPS) for funding in his research. As page limitation precluded us from citing a large number of studies, we apologize to those whose original publications are therefore not directly referenced in this chapter.

References

Allen, D. J., & Ort, D. R. (2001). Impacts of chilling temperatures on photosynthesis in warm-climate plants. *Trends in plant science, 6*(1), 36–42.

Abbas, S. M. (2012). Effects of low temperature and selenium application on growth and the physiological changes in sorghum seedlings. *Journal of Stress Physiology & Biochemistry, 8*, 268–286.

Abdel-Motagally, F. M. F., & El-Zohri, M. (2016). Improvement of wheat yield grown under drought stress by boron foliar application at different growth stages. *Journal of the Saudi Society of Agricultural Sciences*. doi:10.1016/j.jssas.2016.03.005.

Aghaee, A., Moradi, F., Zare-maivan, H., Zarinkamar, F., Irandoost, H. P., & Sharifi, P. (2011). Physiological responses of two rice (*Oryza sativa* L.) genotypes to chilling stress at seedling stage. *African Journal of Biotechnology, 10*, 7617–7621.

Ahmad, F., Rahmatullah, Aziz, T., Maqsood, M. A., Tahir, M. A., & Kanwal, S. (2007). Effect of silicon application on wheat (*Triticum aestivum* L.) growth under water deficiency stress. *Emirates Journal of Food and Agriculture, 19*, 17.

Ahmad, P., Jamsheed, S., & Hameed, A. (2014). *Drought stress induced oxidative damage and antioxidants in plants*. New York: Elsevier.

Ahmed, M., Asif, M., & Goyal, A. (2012). Silicon the non-essential beneficial plant nutrient to enhanced drought tolerance in wheat. In A. Goyal (Ed.), *Crop plant* (pp. 31–48). Rijeka: InTech.

Ahmed, M., Hassen, F., Qadeer, U., & Aslam, M. A. (2011). Silicon application and drought tolerance mechanism of sorghum. *African Journal of Agricultural Research, 6*, 594–607.

Aissa, N., Malagoli, M., & Radhouane, L. (2016). An approach to alleviate the impact of drought stress with selenium amendment. *Iranian Journal of Science and Technology, Transactions A: Science*. (in press).

Ajithkumar, I. P., & Panneerselvam, R. (2013). Osmolyte accumulation, photosynthetic pigment and growth of *Setaria italica* (L) P. Beauv. under drought stress. *Asian Pacific Journal of Reproduction, 2*, 220–224.

Akladious, S. A. (2012). Influence of different soaking times with selenium on growth, metabolic activities of wheat seedlings under low temperature stress. *African Journal of Biotechnology, 11*, 14792–14804.

Akman, Z. (2009). Comparison of high temperature tolerance in maize, rice and sorghum seeds by plant growth regulators. *Journal of Animal and Veterinary Advances, 8*, 358–361.

Aktaş, H., Abak, K., Öztürk, L., & Çakmak, I. (2006). The effect of zinc on growth and shoot concentrations of sodium and potassium in pepper plants under salinity stress. *Turkish Journal of Agriculture and Forestry, 30*, 407–412.

Allakhverdiev, S. I., Kreslavski, V. D., Klimov, V. V., Los, D. A., Carpentier, R., & Mohanty, P. (2008). Heat stress: An overview of molecular responses in photosynthesis. *Photosynthesis Research, 98*, 541–550.

Amirjani, M. R. (2011). Effect of salinity stress on growth, sugar content, pigments and enzyme activity of rice. *International Journal of Botany, 7*, 73–81.

Andaya, V. C., & Mackill, D. J. (2003). QTLs conferring cold tolerance at the booting stage of rice using recombinant inbred lines from a japonica × indica cross. *Theoretical and Applied Genetics, 106*(6), 1084–1090.

Angadi, S. V., Cutforth, H. W., & McConkey, B. G. (2000) Seeding management to reduce temperature stress in *Brassica* species. *Saskatchewan Soils and Crops Proceedings*.

Apel, K., & Hirt, H. (2004). Reactive oxygen species: Metabolism, oxidative stress and signal transduction. *Annual Review of Plant Biology, 55*, 373–399.

Arazi, T., Sunkar, R., Kaplan, B., & Fromm, H. (1999). A tobacco plasma membrane calmodulin-binding transporter confers Ni^{2+} tolerance and Pb^{2+} hypersensitivity in transgenic plants. *The Plant Journal, 20*, 171–182.

Arbona, V., Hossain, Z., López-Climent, M. F., Pérez-Clemente, R. M., & Gómez-Cadenas, A. (2008). Antioxidant enzymatic activity is linked to waterlogging stress tolerance in citrus. *Physiologia Plantarum, 132*, 452–466.

Aroca, R., Vernieri, P., Irigoyen, J. J., Sánchez-díaz, M., Tognoni, F., & Pardossi, A. (2003). Involvement of abscisic acid in leaf and root of maize (*Zea mays* L.) in avoiding chilling induced water stress. *Plant Science, 165*, 671–679.

Arya, S. K., & Roy, B. K. (2011). Manganese induced changes in growth, chlorophyll content and antioxidants activity in seedlings of broad bean (*Vicia faba* L.) *Journal of Environmental Biology, 32*, 707–711.

Ashraf, M., Afzal, R. M., Ahmed, R., Mujeeb, F., Sarwar, A., & Ali, L. (2010). Alleviation of detrimental effects of NaCl by silicon nutrition in salt-sensitive and salt-tolerant genotypes of sugarcane (*Saccharum officinarum* L.) *Plant and Soil, 326*, 381–391.

Ashraf, M., & Harris, P. J. C. (2013). Photosynthesis under stressful environments: An overview. *Photosynthetica, 51*, 163–190.

Azooz, M. M., Abou-Elhamd, M. F., & Al-Fredan, M. A. (2012). Biphasic effect of copper on growth, proline, lipid peroxidation and antioxidant enzyme activities of wheat (*Triticum aestivum* cv. Hasaawi) at early growing stage. *Australian Journal of Crop Science, 6*, 688–694.

Bailey-Serres, J., & Colmer, T. D. (2014). Plant tolerance of flooding stress–recent advances. *Plant, Cell & Environment, 37*, 2211–2215.

Banerjee, S., Dey, N., & Adak, M. K. (2015). Assessment of some biomarkers under submergence stress in some rice cultivars varying in responses. *American Journal of Plant Sciences, 6*, 84–94.

Barnabás, B., Jager, K., & Feher, A. (2008). The effect of drought and heat stress on reproductive processes in cereals. *Plant, Cell & Environment, 31*, 11–38.

Barta, C., Ka'lai, T., Hideg, K., Vass, I., & Hideg, E. (2004). Differences in the ROS-generating efficacy of various ultraviolet wavelengths in detached spinach leaves. *Functional Plant Biology, 31*, 23–28.

Bartling, D., Radzio, R., Steiner, U., & Weiler, E. W. (1993). A glutathione-S transferase with glutathione-peroxidase-activity from *Arabidopsis thaliana*-molecular cloning and functional characterization. *European Journal of Biochemistry, 216*, 579–586.

Biedermann, S., Mooney, S., & Hellmann, H. (2011). Recognition and repair pathways of damaged DNA in higher plants. In C. Chen (Ed.), *Selected topics in DNA repair* (pp. 201–236). Rijeka: InTech.

Biswas, D. K., & Jiang, G. M. (2011). Differential drought induced modulation of ozone tolerance in winter wheat species. *Journal of Experimental Botany, 62*, 4153–4162.

Biswas, D. K., Xu, H., Li, Y. G., Liu, M. Z., & Chen, Y. H. (2008). Assessing the genetic relatedness of higher ozone sensitivity of modern wheat to its wild and cultivated progenitors/relatives. *Journal of Experimental Botany, 59*, 951–963.

Black, V. J., Black, C. R., Roberts, J. A., & Stewart, C. A. (2000). Impact of ozone on the reproductive development of plants. *The New Phytologist, 147*, 421–447.

Blaha, G., Stelzl, U., Spahn, C. M. T., Agrawal, R. K., Frank, J., & Nierhaus, K. H. (2000). Preparation of functional ribosomal complexes and effect of buffer conditions on tRNA positions observed by cryoelectron microscopy. *Methods in Enzymology, 317*, 292–306.

Blevins, D. G., & Lukaszewski, K. M. (1994). Proposed physiologic functions of boron in plants pertinent to animal and human metabolism. *Environmental Health Perspectives, 7*, 31–33.

Blokhina, O., & Fagerstedt, K. V. (2010). Reactive oxygen species and nitric oxide in plant mitochondria: Origin and redundant regulatory systems. *Physiologia Plantarum, 138*, 447–462.

Bordi, A. (2010). The influence of salt stress on seed germination, growth and yield of canola cultivars. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 38*, 128–133.

Brosche, M., Merilo, E., Mayer, F., Pechter, P., & Puzorjova, I. (2010). Natural variation in ozone sensitivity among *Arabidopsis thaliana* accessions and its relation to stomatal conductance. *Plant, Cell & Environment, 33*, 914–925.

Budak, H., Kantar, M., & Yucebilgili Kurtoglu, K. (2013). Drought tolerance in modern and wild wheat. *Scientific World Journal*. doi:10.1155/2013/548246.

Buriro, M., Oad, F. C., Keerio, M. I., Tunio, S., Gandahi, A. W., Hassan, S. W. U., & Oad, S. M. (2011). Wheat seed germination under the influence of temperature regimes. *Sarhad Journal of Agriculture, 27*, 539–543.

Bybordi, A. (2012). Effect of ascorbic acid and silicium on photosynthesis, antioxidant enzyme activity, and fatty acid contents in canola exposure to salt stress. *Journal of Integrative Agriculture, 11*, 1610–1620.

Calviñoa, P. A., Sadrasc, V. O., & Andradeb, F. H. (2003). Development, growth and yield of late-sown soybean in the southern pampas. *European Journal of Agronomy, 19*, 265–275.

Camejo, D., Rodríguez, P., Morales, M. A., Dell'amico, J. M., Torrecillas, A., & Alarcon, J. J. (2005). High temperature effects on photosynthetic activity of ´ two tomato cultivars with different heat susceptibility. *Journal of Plant Physiology, 162*, 281–289.

Cartes, P., Jara, A. A., Pinilla, L., Rosas, A., & Mora, M. L. (2010). Selenium improves the antioxidant ability against aluminium-induced oxidative stress in rye grass roots. *The Annals of Applied Biology, 156*, 297–307.

Chen, M., Chen, Q. J., Niu, X. G., Zhang, R., Lin, H. Q., CY, X., Wang, X. C., Wang, G. Y., & Chen, J. (2007). Expression of OsNHX1 gene in maize confers salt tolerance and promotes plant growth in the field. *Plant, Soil and Environment, 53*(11), 490–498.

Cheng, L., Zou, Y., Ding, S., Zhang, J., Yu, X., Cao, J., & Lu, G. (2009). Polyamine accumulation in transgenic tomato enhances the tolerance to high temperature stress. *Journal of Integrative Plant Biology, 51*, 489–499.

Chinnusamy, V., Zhu, J., & Zhu, J. K. (2007). Cold stress regulation of gene expression in plants. *Trends in Plant Science, 12*, 444–451.

Chu, I., Yao, X., & Zhang, Z. (2010). Responses of wheat seedlings to exogenous selenium supply under cold stress. *Biological Trace Element Research, 136*, 355–363.

Ciscar, J. C. (2012). The impacts of climate change in Europe (the PESETA research project). *Climatic Change, 112*, 1–6.

Cole, P., & McCloud, P. (1985). Salinity and climatic effects on the yields of citrus. *Australian Journal of Experimental Agriculture, 25*, 711–717.

Condon, A. G., Richards, R. A., Rebetzke, G. J., & Farquhar, G. D. (2004). Breeding for high water-use efficiency. *Journal of Experimental Botany, 55*, 2447–2460.

Costa, H., Gallego, S. M., & Tomaro, M. L. (2002). Effects of UV-B radiation on antioxidant defense system in sunflower cotyledons. *Plant Science, 162*(6), 939–945.

Cramer, G. R., & Nowak, R. S. (1992). Supplemental manganese improves the relative growth, net assimilation and photosynthetic rates of salt-stressed barley. *Physiologia Plantarum, 84*, 600–605.

Cvikrová, M., Gemperlová, L., Martincová, O., & Vanková, R. (2013). Effect of drought and combined drought and heat stress on polyamine metabolism in proline-over-producing tobacco plants. *Plant Physiology and Biochemistry, 73*, 7–15.

Dai, Q., Yan, B., Huang, S., Liu, X., & Peng, S. (1997). Response of oxidative stress defense system in rice (*Oryza Sativa*) leaves with supplemental UV-B radiation. *Physiologia Plantarum, 101*, 301–308.

Damanik, R. I., Maziah, M., Ismail, M. R., Ahmad, S., & Zain, A. M. (2010). Responses of the antioxidative enzymes in Malaysian rice (*Oryza sativa* L.) cultivars under submergence condition. *Acta Physiologiae Plantarum, 32*, 739–747.

Dantas, B. F., De Sa Ribeiro, L., & Aragao, C. A. (2007). Germination, initial growth and cotyledon protein content of bean cultivars under salinity stress. *Revista Brasileira de Sementes, 29*, 106–110.

Datnoff, L. E., Synder, G. H., & Korndörfer, G. H. (2001). *Silicon in agriculture, studies in plant sciences* (Vol. 40). Dordrecht, Netherlands: Elsevier.

Diao, M., Ma, L., Wang, J., Cui, J., Fu, A., & Liu, H.-Y. (2014). Selenium promotes the growth and photosynthesis of tomato seedlings under salt stress by enhancing chloroplast antioxidant defense system. *Journal of Plant Growth Regulation, 33*, 671–682.

Djanaguiraman, M., Devi, D. D., Shanker, A. K., Sheeba, A., & Bangarusamy, U. (2005). Selenium-an antioxidative protectant in soybean during senescence. *Plant and Soil, 272*, 77–86.

Djanaguiraman, M., Prasad, P. V. V., & Seppanen, M. (2010). Selenium protects sorghum leaves from oxidative damage under high temperature stress by enhancing antioxidant defense system. *Plant Physiology and Biochemistry, 48*, 999–1007.

Doncheva, S., Poschenrieder, C., Stoyanova, Z., Georgieva, K., Velichkova, M., & Barceló, J. (2009). Silicon amelioration of manganese toxicity in Mn-sensitive and Mn-tolerant maize varieties. *Environmental and Experimental Botany, 65*, 189–197.

Du, H., Liang, Y., Pei, K., & Ma, K. (2011). UV radiation-responsive proteins in rice leaves: A proteomic analysis. *Plant & Cell Physiology, 52*, 306–316.

Ducic, T., & Polle, A. (2005). Transport and detoxification of manganese and copper in plants. *Brazilian Journal of Plant Physiology, 17*, 103–112.

Dupuis, L., & Dumas, C. (1990). Influence of temperature stress on in vitro fertilization and heat shock protein synthesis in maize (*Zea mays* L.) reproductive systems. *Plant Physiology, 94*, 665–670.

Ebrahimian, E., & Bybordi, A. (2011). Exogenous silicium and zinc increase antioxidant enzyme activity and alleviate salt stress in leaves of sunflower. *Journal of Food, Agriculture and Environment, 9*, 422–427.

Ekelund, N. G. A., & Danilov, R. A. (2001). The influence of selenium on photosynthesis and "light-enhanced dark respiration" (LEDR) in the flagellate *Euglena gracilis* after exposure to ultraviolet radiation. *Aquatic Sciences, 63*, 57465.

Ella, E. S., Kawano, N., & Ito, O. (2003). Importance of active oxygen-scavenging system in the recovery of rice seedlings after submergence. *Plant Science, 165*, 85–93.

Elstner, E. F. (1991). Mechanisms of oxygen activation in different compartments of plant cells. In E. J. Pell & K. L. Steffen (Eds.), *Active oxygen/oxidative stress and plant metabolism* (pp. 13–25). Rockville, MD: American Society of Plant Physiology.

Fabiano, C. C., Tezotto, T., Favarin, J. L., Polacco, J. C., & Mazzafera, P. (2015). Essentiality of nickel in plants: A role in plant stresses. *Frontiers in Plant Science, 6*, 754. doi:10.3389/fpls.2015.00754.

Farooq, M., Aziz, T., Wahid, A., Lee, D. J., & Siddique, K. H. M. (2009). Chilling tolerance in maize: Agronomic and physiological approaches. *Crop & Pasture Science, 60*, 501–516.

Farooq, M. A., Detterbeck, A., Clemens, S., & Dietz, K.-J. (2016). Silicon-induced reversibility of cadmium toxicity in rice. *Journal of Experimental Botany, 67*(11), 3573–3585. doi:10.1093/jxb/erw175.

Feng, J., Shi, Q., Wang, X., Wei, M., Yang, F., & Xu, H. (2010). Silicon supplementation ameliorated the inhibition of photosynthesis and nitrate metabolism by cadmium (cd) toxicity in *Cucumis sativus* L. *Scientia Horticulturae, 123*, 521–530.

Feng, Z., Pang, J., Kobayashi, K., Zhu, Z. N., & Ort, D. R. (2011). Differential responses in two varieties of winter wheat to elevated ozone concentration under fully open-air field conditions. *Global Change Biology, 17*, 580–591.

Filek, M., Keskinen, R., Hartikainen, H., Szarejko, I., Janiak, A., Miszalski, Z., & Golda, A. (2008). The protective role of selenium in rape seedlings subjected to cadmium stress. *Journal of Plant Physiology, 165*, 833–844.

Fisarakis, I., Chartzoulakis, K., & Stavrakas, D. (2001). Response of sultana vines (*V. vinifera* L.) on six rootstocks to NaCl salinity exposure and recovery. *Agricultural Water Management, 51*, 13–27.

Foster, K. W., Timm, H., Labanauskas, C. K., & Oshima, R. J. (1983). Effects of ozone and sulfur dioxide on tuber yield and quality of potatoes. *Journal of Environmental Quality, 12*, 75–80.

Fu, X. Z., Xing, F., Wang, N. Q., Peng, L. Z., Chun, C. P., Cao, L., Ling, L. L., & Jiang, C. L. (2014). Exogenous spermine pretreatment confers tolerance to combined high-temperature and drought stress in vitro in trifoliate orange seedlings via modulation of antioxidative capacity and expression of stress-related genes. *Biotechnology and Biotechnological Equipment, 28*, 192–198.

Gao, S. R., Yan, M., Cao, W., Yang, S., Wang, F., & Chen, F. (2008). Effects of copper on growth, antioxidant enzymes and phenylalanine ammonia-lyase activities in *Jatropha curcas* L. seedling. *Plant, Soil and Environment, 54*(3), 117–122.

Gao, W., Zheng, Y., Slusser, J. R., Heisler, G. M., Grant, R. H., Xu, J., & He, D. (2004). Effects of supplementary ultraviolet-B irradiance on maize yield and qualities: A field experiment. *Photochemistry and Photobiology, 80*, 127–131.

García-Sánchez, F., Syvertsen, J. P., Gimeno, V., Botia, P., & Pérez- Pérez, J. G. (2007). Responses to flooding and drought stress by two citrus root stock seedlings with different water-use efficiency. *Physiologia Plantarum, 130*, 532–542.

Gherardi, M., & Rengel, Z. (2003). Genotypes of lucerne (*Medicago sativa* L.) show differential tolerance to manganese deficiency and toxicity when grown in bauxite residue sand. *Plant and Soil, 249*, 287–296.

Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry, 48*, 909–930.

Gillespie, K. M., Rogers, A., & Ainsworth, E. A. (2011). Growth at elevated ozone or elevated carbon dioxide concentration alters antioxidant capacity and response to acute oxidative stress in soybean (*Glycine max*). *Journal of Experimental Botany, 62*(8), 2667–2678. doi:10.1093/jxb/erq435.

Gomes-Filho, E., Machado Lima, C. R. F., Costa, J. H., da Silva, A. C., Guia Silva, d., Lima, M., de Lacerda, C. F., & Prisco, J. T. (2008). Cowpea ribonuclease: Properties and effect of NaCl-salinity on its activation during seed germination and seedling establishment. *Plant Cell Reports, 27*, 147–157.

Goto, M., Ehara, H., Karita, S., Takabe, K., Ogawa, N., & Yamada, Y. (2003). Protective effect of silicon on phenolic biosynthesis and ultraviolet spectral stress in rice crop. *Plant Science, 164*, 349–356.

Greenberg, B. M., Wilson, M. I., Gerhardt, K. E., & Wilson, K. E. (1996). Morphological and physiological responses of *Brassica napus* to ultraviolet radiation: Photomodification of ribulose 1-5- bis phosphate Carboxilase/oxygenase and potential acclimation processes. *Plant Physiology, 148*, 78–85.

Guerinot, M. L. (2000). The ZIP family of metal transporters. *Biochimica et Biophysica Acta—Biomembranes, 1465*, 190–198.

Habibi, G. (2016). Effect of foliar-applied silicon on photochemistry, antioxidant capacity and growth in maize plants subjected to chilling stress. *Acta Agriculturae Slovenica, 107*, 33–43.

Hafeez, B., Khanif, Y. M., & Saleem, M. (2013). Role of zinc in plant nutrition: A review. *American Journal of Agricultural Economics, 3*, 374–391.

Hajiboland, R., Sadeghzadeh, N., Ebrahimi, N., Sadeghzadeh, B., & Mohammadi, S. A. (2016). Influence of selenium in drought-stressed wheat plants under green house and field conditions. *Acta Agriculturae Slovenica, 105*, 175–191.

Hartmann, H. T., Kester, D. E., Davies, F. T. J., & Geneve, R. L. (1997). *Plant propagation principles and practices* (p. 770). Upper Saddle River, NJ: Prentice Hall.

Hasanuzzaman, M. & Fujita, M. (2011). Exogenous silicon treatment alleviates salinity-induced damage in *Brassica napus L.* seedlings by up-regulating the antioxidant defense and methylglyoxal detoxification system. *Abstract of Plant Biology 2011*, American Society of Plant Biology. Retrieved February 12, 2003, from http://abstracts.aspb.org/pb2011/public/P10/P10001.html/.

Hasanuzzaman, M., & Fujita, M. (2012a). Heavy metals in the environment: Current status, toxic effects on plants and possible phytoremediation. In N. A. Anjum, M. A. Pereira, I. Ahmad, A. C. Duarte, S. Umar, & N. A. Khan (Eds.), *Phytotechnologies: Remediation of environmental contaminants* (pp. 7–73). Boca Raton, FL: CRC Press.

Hasanuzzaman, M., & Fujita, M. (2012b). Selenium and plants' health: The physiological role of selenium. In C. Aomori & M. Hokkaido (Eds.), *Selenium: Sources, functions and health effects* (pp. 101–122). New York: Nova Science Publishers.

Hasanuzzaman, M., & Fujita, M. (2013). Exogenous sodium nitroprusside alleviates arsenic-induced oxidative stress in wheat (*Triticum aestivum* L.) seedlings by enhancing antioxidant defense and glyoxalase system. *Ecotoxicology, 22*, 584–596.

Hasanuzzaman, M., Fujita, M., Islam, M. N., Ahamed, K. U., & Nahar, K. (2009). Performance of four irrigated rice varieties under different levels of salinity stress. *International Journal of Integrative Biology, 6*, 85–90.

Hasanuzzaman, M., Hossain, M. A., & Fujita, M. (2010). Selenium in higher plants: Physiological role, antioxidant metabolism and abiotic stress tolerance. *Journal of Plant Science, 5*, 354–375.

Hasanuzzaman, M., Hossain, M. A., & Fujita, M. (2011a). Nitric oxide modulates antioxidant defense and the methylglyoxal detoxification system and reduces salinity-induced damage of wheat seedlings. *Plant Biotechnology Reports, 5*, 353–365.

Hasanuzzaman, M., Hossain, M. A., & Fujita, M. (2011b). Selenium-induced up-regulation of the antioxidant defense and methylglyoxal detoxification system reduces salinity-induced damage in rapeseed seedlings. *Biological Trace Element Research, 143*, 1704–1721.

Hasanuzzaman, M., Hossain, M. A., da Silva, J. A. T., & Fujita, M. (2012a). Plant responses and tolerance to abiotic oxidative stress: Antioxidant defense is a key factor. In V. Bandi, A. K. Shanker, C. Shanker, & M. Mandapaka (Eds.), *Crop stress and its management: Perspectives and strategies* (pp. 261–316). Berlin: Springer.

Hasanuzzaman, M., Hossain, M. A., & Fujita, M. (2012b). Exogenous selenium pretreatment protects rapeseed seedlings from cadmium-induced oxidative stress by upregulating the antioxidant defense and methylglyoxal detoxification systems. *Biological Trace Element Research, 149*, 248–261.

Hasanuzzaman, M., Nahar, K., & Fujita, M. (2013a). Plant response to salt stress and role of exogenous protectants to mitigate salt-induced damages. In P. Ahmad, M. M. Azooz, & M. N. V. Prasad (Eds.), *Ecophysiology and responses of plants under salt stress* (pp. 25–87). New York: Springer.

Hasanuzzaman, M., Nahar, K., & Fujita, M. (2013b). Extreme temperatures, oxidative stress and antioxidant defense in plants. In K. Vahdati & C. Leslie (Eds.), *Abiotic stress—plant responses and applications in agriculture* (pp. 169–205). Rijeka: InTech. doi:10.5772/54833.

Hasanuzzaman, M., Nahar, K., Fujita, M., Ahmad, P., Chandna, R., Prasad, M. N. V., & Ozturk, M. (2013c). Enhancing plant productivity under salt stress: Relevance of poly-omics. In P. Ahmad,

M. M. Azooz, & M. N. V. Prasad (Eds.), *Salt stress in plants: Signaling, omics and adaptations* (pp. 113–156). New York: Springer.

Hasanuzzaman, M., Gill, S. S., & Fujita, M. (2013d). Physiological role of nitric oxide in plants grown under adverse environmental conditions. In N. Tuteja & S. S. Gill (Eds.), *Plant acclimation to environmental stress* (pp. 269–322). New York: Springer. doi:10.1007/978-1-4614-5001-6_11.

Hasanuzzaman, M., Alam, M. M., Rahman, A., Hasanuzzaman, M., Nahar, K., & Fujita, M. (2014a). Exogenous proline and glycine betaine mediated upregulation of antioxidant defense and glyoxalase systems provides better protection against salt-induced oxidative stress in two rice (*Oryza sativa* L.) varieties. *BioMed Research International, 2014*, 757219. doi:10.1155/2014/757219.

Hasanuzzaman, M., Nahar, K., & Fujita, M. (2014b). Silicon and selenium: Two vital trace elements in conferring abiotic stress tolerance to plants. In A. Parvaiz & S. I. Rasool (Eds.), *Emerging technologies and management of crop stress tolerance*, *Biological techniques* (Vol. 1, pp. 375–420). New York: Academic Press.

Hasanuzzaman, M., Nahar, K., Gill, S. S., & Fujita, M. (2014c). Drought stress responses in plants, oxidative stress, and antioxidant defense. In N. Tuteja & S. S. Gill (Eds.), *Climate change and plant abiotic stress tolerance* (pp. 209–250). Germany: Wiley-Blackwell. doi:10.1002/9783527675265.ch09.

Hasanuzzaman, M., Nahar, K., & Fujita, M. (2015). Arsenic toxicity in plants and possible remediation. In K. R. Hakeem, M. Sabir, M. Ozturk, & A. Murmet (Eds.), *Soil remediation and plants: Prospects and challenges* (pp. 433–501). Amsterdam: Elsevier.

Hasanuzzaman, M., Nahar, K., Rahman, A., Mahmud, J. A., Hossain, M. S., & Fujita, M. (2016). Soybean production and environmental stresses. In M. Miransari (Ed.), *Environmental stresses in soybean production: Soybean production* (Vol. 2, pp. 61–102). New York: Elsevier.

Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., Thomson, A. M., & Wolfe, D. W. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal, 103*, 351–370.

Hawrylak-Nowak, B. (2009). Beneficial effects of exogenous selenium in cucumber seedlings subjected to salt stress. *Biological Trace Element Research, 132*, 259–269.

Hawrylak-Nowak, B. (2015). Selenite is more efficient than selenate in alleviation of salt stress in lettuce plants. *Acta Biologica Cracoviensia Series Botanica, 57*, 49–54.

Hawrylak-Nowak, B., Matraszek, R., & Szyma'nska, M. (2010). Selenium modifies the effect of short-term chilling stress on cucumber plants. *Biological Trace Element Research, 138*, 307–315.

Hedhly, A. (2011). Sensitivity of flowering plant gametophytes to temperature fluctuations. *Environmental and Experimental Botany, 74*, 9–16.

Hedhly, A., Hormaza, J. I., & Herrero, M. (2009). Global warming and sexual plant reproduction. *Trends in Plant Science, 14*, 30–36.

Herrera-Rodríguež, M. B., González-Fontes, A., Rexach, J., Camacho-Cristóbal, J. J., Maldonado, J. M., & Navarro-Gochicoa, M. T. (2010). Role of boron in vascular plants and mechanisms to boron stresses. *Plant Stress, 4*(2), 115–122.

Heyno, E., Mary, V., Schopfer, P., & Krieger-Liszkay, A. (2011). Oxygen activation at the plasma membrane: Relation between superoxide and hydroxyl radical production by isolated membranes. *Planta, 234*, 35–45.

Hirschi, K. D., Korenkov, V. D., Wilganowski, N. L., & Wagner, G. J. (2000). Expression of *Arabidopsis CAX2* in tobacco altered metal accumulation and increased manganese tolerance. *Plant Physiology, 124*, 125–133.

Hossain, M. M., Liu, X., & Qi, X. (2014). Differences between soybean genotypes in physiological response to sequential soil drying and rewetting. *The Crop Journal, 2*, 1–15. doi:10.1016/j.cj.2014.08.001.

Hossain, Z., López-Climent, M. F., Arbona, V., Pérez-Clemente, R. M., & Gómez-Cadenas, A. (2009). Modulation of the antioxidant system in citrus under waterlogging and subsequent drainage. *Journal of Plant Physiology, 166*, 1391–1404.

Hu, W. H., Song, X. S., Shi, K., Xia, X. J., Zhou, Y. H., & JQ, Y. (2008). Changes in electron transport, superoxide dismutase and ascorbate peroxidase isoenzymes in chloroplasts and mitochondria of cucumber leaves as influenced by chilling. *Photosynthetica, 46*, 581–588.

Hurry, V. M., Malmberg, G., Gardestorm, P., & Oquist, G. (1994). Effects of a short term shift to low temperature and of long term cold hardening on photosynthesis and ribulose-1, 5- bisphosphate carboxylase/oxygenase and sucrose phosphate activity in leaves of winter rye (*Secale cereale* L.) *Plant Physiology, 106*, 983–990.

IPCC. (2008). Climate change and water. In B. C. Bates, Z. W. Kundzewicz, J. Palutikof, & S. Wu (Eds.), *Technical paper of the intergovernmental panel for climate change* (p. 210). Geneva: Secretariat.

Iqbal, M., Hussain, I., Liaqat, H., Ashraf, M. A., Rasheed, R., & Rehman, A. U. (2015). Exogenously applied selenium reduces oxidative stress and induces heat tolerance in spring wheat. *Plant Physiology and Biochemistry, 94*, 95–103.

Irfan, M., Hayat, S., Hayat, O., Afroz, S., & Ahmad, A. (2010). Physiological and biochemical changes in plants under waterlogging. *Protoplasma, 241*, 3–17.

Ismail, A. M., & Hall, A. E. (1999). Reproductive-stage, heat tolerance, leaf membrane thermostability and plant morphology in cowpea. *Crop Science, 39*, 1762–1768.

Jackson, M. B., & Ram, P. C. (2003). Physiological and molecular basis of susceptibility and tolerance of rice. *Annals of Botany, 91(2)*, 227–241.

Jain, M., Prasad, P. V. V., Boote, K. J., Hartwell, A. L., & Chourey, P. S. (2007). Effects of season-long high temperature growth conditions on sugar-to-starch metabolism in developing microspores of grain sorghum (*Sorghum bicolor* L). *Planta, 227*, 67–79.

James, R. A., von Caemmerer, S., Condon, A. G., Zwart, A. B., & Munns, R. (2008). Genetic variation in tolerance to the osmotic stress component of salinity stress in durum wheat. *Functional Plant Biology, 35*, 111–123.

Janislampi, K. W. (2012). Effect of silicon on plant growth and drought stress tolerance. M.S. thesis, Department of Plants, Soils, and Climate, Utah State University. Retrieved February 11, 2013, from http://digitalcommons.usu.edu/etd/1360/.

Javadmanesh, S., Rahmani, F., & Pourakbar, L. (2012). UV-B radiation, soil salinity, drought stress and their concurrent effects on some physiological parameters in maize plant American-Eurasian. *The Journal of Toxicological Sciences, 4*(4), 154–164.

Jiang, Q. W., Kiyoharu, O., & Ryozo, I. (2002). Two novel mitogen-activated protein signaling components, *OsMEK1* and *OsMAP1*, are involved in a moderate low-temperature signaling pathway in Rice. *Plant Physiology, 129*, 1880–1891.

Kalbarczyk, R. (2009). Potential reduction in cucumber yield (*Cucumis sativus* L.) in poland caused by unfavourable thermal conditions of soil. *Acta Scientiarum Polonorum Hortorum Cultus, 8*, 45–58.

Kalisz, A., & Cebula, S. (2001). Direct plant covering and soil mulching in the spring production of some Chinese cabbage cultivars. Effect of temperature on premature bolting. *Folia Horticulturae, 13*, 13–22.

Kato, Y., Miwa, K., Takano, J., Wada, M., & Fujiwara, T. (2009). Highly boron deficiency tolerant plants generated by enhanced expression of *NIP5;1*, a boric acid channel. *Plant & Cell Physiology, 50*, 58–66.

Kaveh, H., Nemati, H., Farsi, M., & Jartoodeh, S. V. (2011). How salinity affect germination and emergence of tomato lines. *Journal of Biological and Environmental Sciences, 5*, 159–163.

Kesselmeier, J., & Staudt, M. (1999). Biogenic volatile organic compounds (VOC): An overview on emission, physiology and ecology. *Journal of Atmospheric Chemistry, 33*, 23–88.

Khan, M. A., & Weber, D. J. (2008). *Ecophysiology of high salinity tolerant plants (tasks for vegetation science)* (1st ed.). Amsterdam: Springer.

Kong, L., Wang, M., & Bi, D. (2005). Selenium modulates the activities of antioxidant enzymes, osmotic homeostasis and promotes the growth of sorrel seedlings under salt stress. *Plant Growth Regulation, 45*, 155–163.

Krzyzanowski, F. C., & Delouche, J. C. (2011). Germination of cotton seed in relation to temperature. *Revista Brasileira de Farmacognosia, 33*, 543–548.

Kumar, P., Pal, M., Joshi, R., & Sairam, R. K. (2013). Yield, growth and physiological responses of mung bean (*Vigna radiata* L) genotypes to waterlogging at vegetative stage. *Physiology and Molecular Biology of Plants, 19*(2), 209–220.

Kumar, R. R., Goswami, S., Sharma, S. K., Singh, K., Gadpayle, K. A., Kuma, N., Rai, G. K., Singh, M., & Rai, R. D. (2012). Protection against heat stress in wheat involves change in cell membrane stability, antioxidant enzymes, osmolyte, H_2O_2 and transcript of heat shock protein. *International Journal of Plant Physiology and Biochemistry, 4*, 83–91.

Kumutha, D., Ezhilmathi, K., Sairam, R. K., Srivastava, G. C., Deshmukh, P. S., & Meena, R. C. (2009). Waterlogging induced oxidative stress and antioxidant activity in pigeon pea genotypes. *Biologia Plantarum, 53*, 75–84.

Kuznetsov, V. V., Kholodova, V. P., Kuznetsov, V. V., & Yagodin, B. A. (2003). Selenium regulates the water status of plants exposed to drought. *Doklady Biological Sciences, 390*, 266–268.

Latef, A. A. A., & Tran, L.-S. (2016). Impacts of priming with silicon on the growth and tolerance of maize plants to alkaline stress. *Frontiers in Plant Science*. doi:10.3389/fpls.2016.00243.

Lee, H., Guo, Y., Ohta, M., Xiong, L., Stevenson, B., & Zhu, J. K. (2002). LOS_2, a genetic locus required for cold responsive transcription encodes a bifunctional enolase. *The EMBO Journal, 21*, 2692–2702.

Leisner, C. P., Cousins, A. B., Offermann, S., Okita, T. W., & Edwards, G. E. (2010). The effects of salinity on photosynthesis and growth of the single-cell C4 species *Bienertia sinuspersici* (Chenopodiaceae). *Photosynthesis Research, 106*, 201–214.

Li, J., Cang, Z., & Jiao, F. (2015). Influence of drought stress on photosynthetic characteristics and protective enzymes of potato at seedling stage. *Journal of the Saudi Society of Agricultural Sciences*. doi:10.1016/j.jssas.2015.03.001.

Li, M., Li, Y., Li, H., & Wu, G. (2011). Overexpression of AtNHX5 improves tolerance to both salt and drought stress in (*Broussonetia papyrifera* L.) vent. *Tree Physiology, 31*, 349–357. doi:10.1093/treephys/tpr003.

Li, W., Khan, M. A., Yamaguchi, S., & Kamiya, Y. (2005). Effects of heavy metals on seed germination and early seedling growth of *Arabidopsis thaliana*. *Plant Growth Regulation, 46*, 45–50.

Liang, Y., Sun, W., Zhu, Y. G., & Christie, P. (2007). Mechanisms of silicon mediated alleviation of abiotic stresses in higher plants: A review. *Environmental Pollution, 147*, 422–428.

Liang, Y., Zhu, J., Li, Z., Chu, G., Ding, Y., & Zhang, J. (2008). Role of silicon in enhancing resistance to freezing stress in two contrasting winter wheat cultivars. *Environmental and Experimental Botany, 64*, 286–294.

Lidon, F. C., Barreiro, M., & Ramalho, J. (2004). Manganese accumulation in rice: Implications for photosynthetic functioning. *Journal of Plant Physiology, 161*, 1235–1244.

Lin, Y. F., Hassan, Z., Talukdar, S., Schat, H., & Aarts, M. G. M. (2016). Expression of the ZNT1 zinc transporter from the metal Hyperaccumulator Noccaea Caerulescens confers enhanced zinc and cadmium tolerance and accumulation to *Arabidopsis thaliana*. *PloS One, 11*(3), e0149750. doi:10.1371/journal.pone.0149750.

Lindsey, L., & Thomson, P. (2012). High temperature effects on corn and soybean. *C.O.R.N Newsletter, 2012*, 23–26.

Liu, B., Liu, X., Li, Y., & Herbert, S. J. (2013). Effects of enhanced UV-B radiation on seed growth characteristics and yield components in soybean. *Field Crops Research, 154*, 158–163.

Liu, J. J., Lin, S. H., PL, X., Wang, X. J., & Bai, J. G. (2009). Effects of exogenous silicon on the activities of antioxidant enzymes and lipid peroxidation in chilling-stressed cucumber leaves. *Agricultural Sciences in China, 8*, 1075–1086.

Liu, S. J., Heng-Heng, X., Wang, W.-Q., Ni, L., Wang, W.-P., Møller, I. M., & Song, S.-Q. (2014). A proteomic analysis of rice seed germination as affected by high temperature and ABA treatment. *Physiologia Plantarum, 154*, 142–161.

Lombardi, T., & Lupi, B. (2006). Effect of salinity on the germination and growth of Hordeum secalinum Schreber (Poaceae) in relation to the seeds after-ripening time. *Atti Soc tosc Sci nat Mem Serie B, 113*, 37–42.

Long, S. P., & Ort, D. R. (2010). More than taking the heat: Crops and global change. *Current Opinion in Plant Biology, 13*, 240–247.

Luo, H. H., Zhang, Y. L., & Zhang, W. F. (2016). Effects of water stress and rewatering on photosynthesis, root activity, and yield of cotton with drip irrigation under mulch. *Photosynthetica, 54*, 65–73. doi:10.1007/s11099-015-0165-7.

Lyman, N. B., Jagadish, K. S. V., Nalley, L. L., Dixon, B. L., & Siebenmorgen, T. (2013). Neglecting rice milling yield and quality underestimates economic losses from high-temperature stress. *PloS One, 8*, e72157.

Ma, J. F., & Yamaji, N. (2008). Functions and transport of silicon in plants. *Cellular and Molecular Life Sciences, 65*, 3049–3057.

Mahajan, S., & Tuteja, N. (2005). Cold, salinity and drought stresses: An overview. *Archives of Biochemistry and Biophysics, 444*, 139–158.

Maksymiec, W. (2007). Signaling responses in plants to heavy metal stress. *Acta Physiologiae Plantarum, 29*, 177–187.

Manaf, H. H. (2016). Beneficial effects of exogenous selenium, glycine betaine and seaweed extract on salt stressed cowpea plant. *Annals of Agricultural Science, 61*, 41–48.

Manivannan, A., Soundararajan, P., Muneer, S., Ho Ko, C., & Jeong, B. R. (2016). Silicon mitigates salinity stress by regulating the physiology, antioxidant enzyme activities, and protein expression in *Capsicum annuum* 'Bugwang'. *BioMed Research International*. doi:10.1155/2016/3076357.

Marcińska, I., Czyczyło-Mysza, I., & Skrzypek, E. (2013). Impact of osmotic stress on physiological and biochemical characteristics in drought-susceptible and drought-resistant wheat genotypes. *Acta Physiologiae Plantarum, 35*, 451–461. doi:10.1007/s11738-012-1088-6.

Mateos-Naranjo, E., Andrades-Moreno, L., & Davy, A. J. (2013). Silicon alleviates deleterious effects of high salinity on the halophytic grass *Spartina densiflora*. *Plant Physiology and Biochemistry, 63*, 115–121.

Mauad, M., Costa Crusciol, C. A., Nascente, A. S., Filho, H. G., & Lima, G. P. P. (2016). Effects of silicon and drought stress on biochemical characteristics of leaves of upland rice cultivars. *Revista Ciência Agronômica, 47*, 532–539.

McNamara, A. E., & Hill, W. R. (2000). UV-B irradiance gradient affects photosynthesis and pigments but not food quality of perihyton. *Freshwater Biology, 43*, 649–662.

Mditshwa, A., Bower, J. P., Bertling, I., Mathaba, N., & Tesfay, S. Z. (2013). The potential of postharvest silicon dips to regulate phenolics in citrus peel as a method to mitigate chilling injury in lemons. *African Journal of Biotechnology, 12*, 1482–1489.

Migocka, M., Papierniak, A., Maciaszczyk-Dziubińska, E., Poździk, P., Posyniak, E., Garbiec, A., & Filleur, S. (2014). Cucumber metal transport protein MTP8 confers increased tolerance to manganese when expressed in yeast and *Arabidopsis thaliana*. *Journal of Experimental Botany, 65*(18), 5367–5384. doi:10.1093/jxb/eru295.

Millaleo, R., Reyes-Diaz, M., Ivanov, A. G., Mora, M. L., & Alberdi, M. (2010). Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms. *Journal of Soil Science and Plant Nutrition, 10*, 476–449.

Miller, P., Lanier, W., Brandt, S. (2001). Using growing degree days to predict plant stages. Montana State University Extension Service. SKU MT200103AG.

Mithofer, A., Schulze, B., & Boland, W. (2004). Biotic and heavy metal stress response in plants: Evidence for common signals. *FEBS Letters, 566*, 1–5.

Mittler, R. (2002). Oxidative stress, antioxidants and stress tolerance. *Trends in Plant Science, 7*, 405–410.

Mittler, R., & Blumwald, E. (2010). Genetic engineering for modern agriculture: Challenges and perspectives. *Annual Review of Plant Biology, 61*, 443–462.

Mittler, R., Finka, A., & Goloubinoff, P. (2012). How do plants feel the heat? *Trends in Biochemical Sciences, 37*, 118–125.

Moeinian, M. R., Zargari, K., & Hasanpour, J. (2011). Effect of boron foliar spraying application on quality characteristics and growth parameters of wheat grain under drought stress. *American-Eurasian Journal of Agricultural & Environmental Sciences, 10*(4), 593–599.

Monjezi, F., Vazan, F., & Hassnzadehdelouei, M. (2012). Effects of iron and zinc spray on wheat in drought stress. *Cercetări Agronomice în Moldova, XLVI*(1), 153.

Morison, J. I. L., Baker, N. R., Mullineaux, P. M., & Davies, W. J. (2008). Improving water use in crop production. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*, 639–658.

Mozafariyan, M., Kamelmanesh, M. M., & Hawrylak-Nowak, B. (2016). Ameliorative effect of selenium on tomato plants grown under salinity stress. *Archives of Agronomy and Soil Science*. doi:10.1080/03650340.2016.1149816.

Moussa, H. R., & Abdel-Aziz, S. M. (2008). Comparative response of drought tolerant and drought sensitive maize genotypes to water stress. *Australian Journal of Crop Science, 1*(1), 31–36.

Müller-Xing, R., Xing, Q., & Goodrich, J. (2014). Footprints of the sun: Memory of UV and light stress in plants. *Frontiers in Plant Science, 5*, 474.

Munns, R. (2002). Comparative physiology of salt and water stress. *Plant, Cell & Environment, 25*, 239–250.

Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology, 59*, 651–681.

Mustafiz, A., Ghosh, A., Tripathi, A. K., Kaur, C., Ganguly, A. K., Bhavesh, N. S., Tripathi, J. K., Pareek, A., Sopory, S. K., & Singla-Pareek, S. L. (2014). A unique Ni^{2+}-dependent and methylglyoxal-inducible rice glyoxalase I possesses a single active site and functions in abiotic stress response. *The Plant Journal, 78*, 951–963.

Nahar, K., Biswas, J. K., & Shamsuzzaman, A. M. M. (2012). *Cold stress tolerance in rice plant: Screening of genotypes based on morphophysiological traits*. Saarbrücken, Germany: Lambert Academic Publishing.

Nahar, K., Biswas, J. K., Shamsuzzaman, A. M. M., Hasanuzzaman, M., & Barman, H. N. (2009). Screening of indica rice (*Oryza sativa* L.) genotypes against low temperature stress. *Botany Research International, 2*, 295–303.

Nahar, K., & Hasanuzzaman, M. (2009). Germination, growth, nodulation and yield performance of three mungbean varieties under different levels of salinity stress. *Green Farming, 2*, 825–829.

Nahar, K., Hasanuzzaman, M., Alam, M. M., & Fujita, M. (2014). Regulatory roles of exogenous glutathione in conferring salt tolerance in mung bean (*Vigna radiata* L.): Implication of antioxidant defense and methylglyoxal detoxification system. *Biologia Plantarum, 59*, 745–756.

Nahar, K., Hasanuzzaman, M., Ahamed, K. U., Öztürk, M., & Fujita, M. (2015a). Plant responses and tolerance to high temperature stress: Role of exogenous phytoprotectants. In K. U. R. Hakeem (Ed.), *Crop production and global environmental issues* (pp. 385–436). Cham, Switzerland: Springer.

Nahar, K., Hasanuzzaman, M., Alam, M. M., & Fujita, M. (2015b). Exogenous spermidine alleviates low temperature injury in mung bean (*Vigna radiata* L.) seedlings by modulating ascorbate-glutathione and glyoxalase pathway. *International Journal of Molecular Sciences, 16*, 30117–30132.

Nahar, K., Hasanuzzaman, M., Alam, M. M., Rahman, A., Suzuki, T., & Fujita, M. (2016). Polyamine and nitric oxide crosstalk: antagonistic effects on cadmium toxicity in mung bean plants through upregulating the metal detoxification, antioxidant defense and methylglyoxal detoxification systems. *Ecotoxicology and environmental safety, 126*, 245–255.

Nahar, K., Hasanuzzaman, M., Alam, M. M., Rahman, A., Mahmud, J. A., Suzuki, T., & Fujita, M. (2017). Insights into spermine-induced combined high temperature and drought tolerance in mung bean: osmoregulation and roles of antioxidant and glyoxalase system. *Protoplasma, 254(1)*, 445–460.

Naim, A. (2015). *Mitigation of salt stress in rice by exogenous application of selenium*. M.S. thesis, Department of Agronomy, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh.

Nasibi, F., & M-Kalantari, K. H. (2005). The effects of uv-a, uv-b and uv-c on protein and ascorbate content, lipid peroxidation and biosynthesis of screening compounds in *Brassica napus*. *Iranian Journal of Science and Technology, 29*, 40–48.

Nawaz, F., Ashraf, M. Y., Ahmad, R., & Waraich, E. A. (2013). Selenium (Se) seed priming induced growth and biochemical changes in wheat under water deficit conditions. *Biological Trace Element Research, 151*, 284–293.

Nawaz, F., Ashraf, M. Y., Ahmad, R., Waraich, E. A., & Shabbir, R. N. (2014). Selenium (se) regulates seedling growth in wheat under drought stress. *Advances in Chemistry*. doi:10.1155/2014/143567.

Nelson, J. M., Palzkill, D. A., & Bartels, P. G. (1993). Irrigation cut-off date affects growth, frost damage, and yield of jojoba. *Journal of the American Society for Horticultural Science, 118*(6), 731–735.

Nishiuchi, S., Yamauchi, T., Takahashi, H., Kotula, L., & Nakazono, M. (2012). Mechanisms for coping with submergence and waterlogging in rice. *Rice, 5*, 2. doi:10.1186/1939-8433-5-2.

Niu, G., Rodriguez, D. S., Circle, M., et al. (2006). Impact of drought and temperature on growth and leaf gas exchange of six bedding plant species under greenhouse conditions. *Hortscience, 41*, 1408–1411.

Noctor, G., De Paepe, R., & Foyer, C. H. (2007). Mitochondrial redox biology and homeostasis in plants. *Trends in Plant Science, 12*, 125–134.

Noctor, G., Veljovic-Jovanovic, S. O. N. J. A., Driscoll, S., Novitskaya, L., & Foyer, C. H. (2002). Drought and oxidative load in the leaves of C3 plants: a predominant role for photorespiration? *Annals of Botany, 89*(7), 841–850.

Obidiegwu, J. E., Bryan, G. J., Jones, H. G., & Prashar, A. (2015). Coping with drought: Stress and adaptive responses in potato and perspectives for improvement. *Frontiers in Plant Science, 6*, 542. doi:10.3389/fpls.2015.00542.

Othman, Y., Al-Karaki, G., Al-Tawaha, A. R., & Al-Horani, A. (2006). Variation in germination and ion uptake in barley genotypes under salinity conditions. *World Journal of Agricultural Sciences, 2*, 11–15.

Pal'ove-Balang, P., Kisova, A., Pavlovkin, J., & Mistrik, I. (2006). Effect of manganese on cadmium toxicity in maize seedlings. *Plant, Soil and Environment, 52*, 143–149.

Pandey, G. K. (2015). *Elucidation of abiotic stress signaling in plants: Functional genomics perspectives* (Vol. 2). New York: Springer.

Pandya, D. H., Mer, R. K., Prajith, P. K., & Pandey, A. N. (2004). Effect of salt stress and manganese supply on growth of barley seedlings. *Journal of Plant Nutrition, 27*, 1361–1379.

Parveen, N., & Ashraf, M. (2010). Role of silicon in mitigating the adverse effects of salt stress on growth and photosynthetic attributes of two maize (*Zea mays* L.) cultivars grown hydroponically. *Pakistan Journal of Botany, 42*, 1675–1684.

Peacock, J. M., Miller, W. B., Matsuda, K., & Robinson, D. L. (1993). Role of heat girdling in early seedling death in sorghum. *Crop Science, 30*, 138–143.

Pedrero, Z., Madrid, Y., Hartikainen, H., & Cámara, C. (2008). Protective effect of selenium in broccoli (*Brassica oleracea*) plants subjected to cadmium exposure. *Journal of Agricultural and Food Chemistry, 56*, 266–271.

Peng, K., Chunling, L., Wuxin, Y., Chunlan, L., Xiangdong, L., & Shen, Z. (2008). Manganese uptake and interactions with cadmium in the hyperaccumulator-*Phytolacca americana* L. *Journal of Hazardous Materials, 154*, 674–681.

Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., Centeno, G. S., Khush, G. S., & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America, 101*, 9971–9975.

Pennanen, A., Xue, T., & Hartikainen, H. (2002). Protective role of selenium in plant subjected to severe UV irradiation stress. *Journal of Applied Botany, 76*, 66–76.

Pirovano, L., Morgutti, S., Espen, L., & Cocucci, S. M. (1997). Differences in the reactivation process in thermosensitive seeds of *Phacelia tanacetifolia* with germination inhibited by high temperature (30°C). *Physiologia Plantarum, 99*, 211–220.

Pittman, J. (2005). Managing the manganese: Molecular mechanisms of manganese transport and homeostasis. *The New Phytologist, 167*, 733–742.

Porch, T. G. (2006). Application of stress indices for heat tolerance screening of common bean. *Journal of Agronomy and Crop Science, 192*, 390–394.

Prabagar, S., Hodson, M. J., & Evans, D. E. (2011). Silicon amelioration of aluminium toxicity and cell death in suspension cultures of Norway spruce (*Picea abies* L.) *Environmental and Experimental Botany, 70*, 266–276.

Prasad, P. V. V., Pisipati, S. R., Momčilović, I., & Ristic, Z. (2011). Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-Tu expression in spring wheat. *Journal of Agronomy and Crop Science, 197*, 430–441.

Rahman, M. S., Matsumuro, T., Miyake, H., & Takeoka, Y. (2000). Salinity-induced Ultrastructural alterations in leaf cells of rice alternations in leaf cells of rice (*Oryza sativa* L.). *Plant Production Science, 3*, 422–429.

Rahman, A., Mostofa, M. G., Nahar, K., Hasanuzzaman, M., & Fujita, M. (2015). Exogenous calcium alleviates cadmium-induced oxidative stress in rice seedlings by regulating the antioxidant defense and glyoxalase systems. *Brazilian Journal of Botany*. doi:10.1007/s40415-015-0240-0.

Rahman, A., Hossain, M. S., Mahmud, J. A., Nahar, K., Hasanuzzaman, M., & Fujita, M. (2016). Manganese-induced salt stress tolerance in rice seedlings: Regulation of ion homeostasis, antioxidant defense and glyoxalase systems. *Physiology and Molecular Biology of Plants*. doi:10.1007/s12298-016-0371-1.

Ram, P. C., Singh, A. K., Singh, B. B., Singh, V. K., Singh, H. P., Setter, T. L., Singh, V. P., & Singh, R. K. (1999). Environmental characterization of floodwater in eastern India: Relevance to submergence tolerance of lowland rice. *Experimental Agriculture, 35*, 141–152.

Rasolohery, C. A., Berger, M., Lygin, A. V., Lozovaya, V. V., Nelson, R. L., & Dayde, J. (2008). Effect of temperature and water availability during late maturation of the soybean seed on germ and cotyledon isoflavone content and composition. *Journal of Science and Food Agriculture, 88*, 218–228.

Raven, J. A. (2001). Silicon transport at the cell and tissue level. In L. E. Datnoff, G. H. Snyder, & G. H. Korndorfer (Eds.), *Silicon in agriculture* (pp. 41–55). Amsterdam: Elsevier.

Ravindran, K. C., Indrajith, A., Pratheesh, P. V., Sanjiviraja, K., & Balakrishnan, V. (2010). Effect of ultraviolet-B radiation on biochemical and antioxidant defence system in *Indigofera tinctoria* L. seedlings. *International Journal of Engineering Science and Technology, 2*, 226–232.

Raziuddin, Farhatullah, Hassan, G., Akmal, M., Shah, S. S., Mohammad, F., Shafi, M., Bakht, J., & Zhou, W. (2011). Effects of cadmium and salinity on growth and photosynthesis parameters of *Brassica species*. *Pakistan Journal of Botany, 43*, 333–340.

Reddy, K. R., Kakani, V. G., Zhao, D., Mohammed, A. R., & Gao, W. (2003). Cotton responses to ultraviolet-B radiation: Experimentation and algorithm development. *Agricultural and Forest Meteorologyis, 120*, 249–265.

Ren, B., Zhang, J., Li, X., Fan, X., Dong, S., Liu, P., & Zhao, B. (2014). Effects of waterlogging on the yield and growth of summer maize under field conditions. *Canadian Journal of Plant Science, 94*, 23–31.

Riaz-ud-din, Subhani, G. M., Ahmad, N., Hussain, M., & Rehman, A. U. (2010). Effect of temperature on development and grain formation in spring wheat. *Pakistan Journal of Botany, 42*, 899–906.

Riley, G. J. P. (1981). Effects of high temperature on protein synthesis during germination of maize (*Zea mays* L.). *Planta, 151*, 75–80.

Robertson, D., Zhang, H., Palta, J. A., Colmer, T., & Turner, N. C. (2009). Waterlogging affects the growth, development of tillers, and yield of wheat through a severe, but transient, N deficiency. *Crop & Pasture Science, 60*, 578–586.

Sairam, R. K., Dharmar, K., Lekshmy, S., & Chinnusam, V. (2011). Expression of antioxidant defense genes in mung bean (*Vigna radiata* L.) roots under water-logging is associated with hypoxia tolerance. *Acta Physiologiae Plantarum, 33*, 735–744.

Sajedi, N., Madani, H., & Naderi, A. (2011). Effect of microelements and selenium on superoxide dismutase enzyme, malondialdehyde activity and grain yield maize (*Zea mays* L.) under water deficit stress. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 39*, 153–159.

Sakata, T., Oshino, T., Miura, S., Tomabechi, M., Tsunaga, Y., Higashitani, N., Miyazawa, Y., Takahashi, H., Watanabe, M., & Higashitani, A. (2010). Auxins reverse plant male sterility caused by high temperatures. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 8569–8574.

Salim, B. B. M. (2014). Effect of boron and silicon on alleviating salt stress in maize. *Middle East Journal of Agricultural Research, 3*(4), 1196–11204.

Samreen, T., Humaira, & Shah, H. U. (2013). Zinc effect on growth rate, chlorophyll, protein and mineral contents of hydroponically grown mungbeans plant (*Vigna radiata*). *Arabian Journal of Chemistry*. doi:10.1016/j.arabjc.2013.07.005.

Sandalio, L. M., Rodríguez-Serrano, M., Romero-Puertas, M. C., & del Ríıo, L. A. (2013). Role of peroxisomes as a source of reactive oxygen species (ROS) signaling molecules. Del Río LA (ed) peroxisomes and their key role in cellular signaling and metabolism. *Sub-Cellular Biochemistry, 69*, 231–255.

Sanghera, G. S., Wani, S. H., Hussain, W., & Singh, N. B. (2011). Engineering cold stress tolerance in crop plants. *Current Genomics, 12*, 30–43.

Sapeta, H., Costa, J. M., Lourenço, T., Marocod, J., Lindee, P. V., & Oliveiraa, M. M. (2013). Drought stress response in *Jatropha curcas*: Growth and physiology. *Environmental and Experimental Botany, 85*, 76–84.

Sarma, H. (2011). Metal hyperaccumulation in plants: A review focusing on phytoremediation technology. *Journal of Environmental Science and Technology, 4*, 118–138.

Sasaki, A., Yamaji, N., & Ma, J. F. (2016). Transporters involved in mineral nutrient uptake in rice. *Journal of Experimental Botany, 67*(12), 3645–3653. doi:10.1093/jxb/erw060.

Sawada, H., Tsukahara, K., Kohno, Y., Suzuki, K., Nagasawa, N., & Tamaok, M. (2016). Elevated ozone deteriorates grain quality of *Japonica* Rice cv. Koshihikari, even if it does not cause yield reduction. *Rice, 9*, 7.

Sebastian, A., & Prasad, M. N. V. (2015). Iron-and manganese-assisted cadmium tolerance in *Oryza sativa* L.: Lowering of rhizotoxicity next to functional photosynthesis. *Planta, 241*, 1519–1528.

Setter, T. L., & Waters, I. (2003). Review of prospects for germplasm improvement for waterlogging tolerance in wheat, barley and oats. *Plant and Soil, 253*, 1–34.

Shabaan, M. M. (2010). Role of Boron in plant nutrition and human health. *American Journal of Plant Physiology, 5*(5), 224–240.

Shah, N., & Paulsen, G. (2003). Interaction of drought and high temperature on photosynthesis and grain-filling of wheat. *Plant and Soil, 257*, 219–226.

Shahbaz, M., & Ashraf, M. (2013). Improving salinity tolerance in cereals. *Critical Reviews in Plant Sciences, 32*, 237–249.

Sharma, A., Gontia-Mishra, I., & Srivastava, A. K. (2011). Toxicity of heavy metals on germination and seedling growth of *Salicornia brachiata*. *Journal of Phytology, 3*, 33–36.

Sharma, P., & Dubey, R. S. (2007). Involvement of oxidative stress and role of antioxidative defense system in growing rice seedlings exposed to toxic levels of aluminium. *Plant Cell Reports, 26*, 2027–2038.

Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2012). Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *Journal of Botany, 37*, 1–26.

Sharma, P. K., Anand, P., Sankhalkar, S., & Shety, R. (1998). Photochemical and biochemical changes in wheat seedlings exposed to supplementary ultraviolet-B radiation. *Plant Science, 132*, 21–30.

Sharma, S. S., & Dietz, K. J. (2008). The relationship between metal toxicity and cellular redox imbalance. *Trends in Plant Science, 14*, 43–50.

Shekari, F., Abbasi, A., & Mustafavi, S. H. (2015). Effect of silicon and selenium on enzymatic changes and productivity of dill in saline condition. *Journal of the Saudi Society of Agricultural Sciences*. doi:10.1016/j.jssas.2015.11.006.

Shekari, L., Kamelmanesh, M. M., Mozafariyan, M., & Sadeghi, F. (2016). Role of selenium in mitigation of cadmium toxicity in pepper grown in hydroponic condition. *Journal of Plant Nutrition*. doi:10.1080/01904167.2016.1161773.

Shen, X., Zhou, Y., Duan, L., Li, Z., Eneji, A. E., & Li, J. (2010). Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet-B radiation. *Journal of Plant Physiology, 167*, 1248–1252.

Shi, Y., Zhang, Y., Han, W., Feng, R., Hu, Y., Guo, J., & Gong, H. (2016). Silicon enhances water stress tolerance by improving root hydraulic conductance in *Solanum lycopersicum* L. *Frontiers in Plant Science, 7*, 196. doi:10.3389/fpls.2016.00196.

Singh, R., Singh, S., Tripathi, R., & Agrawal, S. B. (2011). Supplemental UV-B radiation induced changes in growth, pigments and antioxidant pool of bean (*Dolichos lablab*) under field conditions. *Journal of Environmental Biology, 32*, 139–145.

Singh, R. K., & Flowers, T. J. (2010). Physiology and molecular biology of the effects of salinity on rice. In *Handbook of plant and crop stress* (pp. 899–939). Boca Raton: CRC Press.

Song, A., Li, Z., Zhang, J., Xue, G., Fan, F., & Liang, Y. (2009). Silicon-enhanced resistance to cadmium toxicity in *Brassica chinensis* L. is attributed to Si-suppressed cadmium uptake and transport and Si-enhanced antioxidant defense capacity. *Journal of Hazardous Materials, 172*, 74–83.

Soylemezoglu, G., Demir, K., Inal, A., & Gunes, A. (2009). Effect of silicon on antioxidant and stomatal response of two grapevine (Vitis Vinifera L.) rootstocks grown in boron toxic, saline and boron toxic-saline soil. *Scientia Horticulturae, 123*, 240–246.

Srivastava, M., Ma, L. Q., Rathinasabapathi, B., & Srivastava, P. (2009). Effects of selenium on arsenic uptake in arsenic hyperaccumulator *Pteris vittata* L. *Bioresource Technology, 100*, 1115–1121.

Steffens, B., Geske, T., & Sauter, M. (2011). Aerenchyma formation in the rice stem and its promotion by H_2O_2. *New Phytologist, 190*, 369–378.

Stone, P. J., & Nicolas, M. E. (1994). Wheat cultivars vary widely in their responses of grain yield and quality to short periods of post-anthesis heat stress. *Australian Journal of Plant Physiology, 21*, 887–900.

Sudhir, P., & Murthy, S. D. S. (2004). Effects of salt stress on basic processes of photosynthesis. *Photosynthetica, 42*, 481–486.

Sun, H. W., Ha, J., Liang, S. X., & Kang, W. J. (2010). Protective role of selenium on garlic growth under cadmium stress. *Communications in Soil Science and Plant Analysis, 41*, 1195–1204.

Sun, Q., Wang, X. R., Ding, S. M., & Yuan, X. F. (2005). Effects of exogenous organic chelators on phytochelatins production and its relationship with cadmium toxicity in wheat (*Triticum aestivum* L.) under cadmium stress. *Chemosphere, 60*, 2–31.

Tadina, N., Germ, M., Kreft, I., Breznik, B., & Gaberščik, A. (2007). Effects of water deficit and selenium on common buckwheat (*Fagopyrum esculentum* Moench.) plants. *Photosynthetica, 45*, 472–476.

Taiz, L., & Zeiger, E. (2006). Stress physiology. In L. Taiz & E. Zeiger (Eds.), *Plant physiology* (5th ed., pp. 671–681). Sunderland: Sinauer Associates.

Tavakkoli, E., Fatehi, F., Coventry, S., Rengasamy, P., & McDonald, G. K. (2011). Additive effects of Na^+ and Cl^- ions on barley growth under salinity stress. *Journal of Experimental Botany, 62*, 2189–2203.

Tavallali, V., Rahemi, M., & Eshghi, S. (2010). Zinc alleviates salt stress and increases antioxidant enzyme activity in the leaves of pistachio (*Pistacia vera* L. "Badami") seedlings. *Turkish Journal of Agriculture and Forestry, 34*, 349–359. doi:10.3906/tar-0905-10.

Terry, N., Zayed, A. M., de Souza, M. P., & Tarun, A. S. (2000). Selenium in higher plants. *Annual Review of Plant Physiology and Plant Molecular Biology, 51*, 401–432.

Thakur, P., Kumar, S., Malik, J. A., Berger, J. D., & Nayyar, H. (2010). Cold stress effects on reproductive development in grain crops, an overview. *Environmental and Experimental Botany, 67*, 429–443.

Thameur, A., Lachiheb, B., & Ferchichi, A. (2012). Drought effect on growth, gas exchange and yield, in two strains of local barley Ardhaoui, under water deficit conditions in southern Tunisia. *Journal of Environmental Management, 113*, 495–500. doi:10.1016/j.jenvman.2012.05.026.

Thomashow, M. F. (1999). Plant cold acclimation: Freezing tolerance genes and regulatory mechanisms. *Annual Review of Plant Physiology and Plant Molecular Biology, 50*, 571–579.

Tiryaki, I., & Keles, H. (2012). Reversal of the inhibitory effect of light and high temperature on germination of *Phacelia tanacetifolia* seeds by melatonin. *Journal of Pineal Research, 52*, 332–339.

Tsukahara, K., Sawada, H., Kohno, Y., Matsuura, T., Mori, I. C., & Terao, T. (2015). Ozone-induced rice grain yield loss is triggered via a change in panicle morphology that is controlled by aberrant panicle organization 1 Gene. *PloS One, 10*, e0123308. doi:10.1371/journal.pone.0123308.

Upadhyaya, H., Dutta, B. K., Sahoo, L., & Panda, S. K. (2012). Comparative effect of Ca, K, Mn and B on post-drought stress recovery in tea (*Camellia sinensis* L.) *American Journal of Plant Sciences, 3*, 443–460.

Vašková, J., Vasko, L., & Kron, I. (2012). Oxidative processes and antioxidative metaloenzymes. In M. A. El-Missiry (Ed.), *Antioxidant enzyme*. Rijeka: InTech. doi:10.5772/50995.

Vorobets, N., & Mykiyevich, I. (2000). Single and combined effects of lead and selenium on sunflower seedlings. *Scientific Workshop on Horticulture and Vegetable Growing, 19*, 390.

Vyšniauskienė, R., & Rančelienė, V. (2014). Effect of UV-B radiation on growth and antioxidative enzymes activity in Lithuanian potato (*Solanum tuberosum* L.) cultivars. *Zemdirbyste-Agriculture, 101*(1), 51–56. doi:10.13080/z-a.2014.101.007.

Wahid, A., Gelani, S., Ashraf, M., & Foolad, M. R. (2007). Heat tolerance in plants: An overview. *Environmental and Experimental Botany, 61*, 199–223.

Wang, C. Q., HJ, X., & Liu, T. (2011). Effect of selenium on ascorbate–glutathione metabolism during PEG-induced water deficit in *Trifolium repens* L. *Journal of Plant Growth Regulation, 30*, 436–444.

Wang, L. J., & Li, S. H. (2006). Salicylic acid-induced heat and cold tolerance in relation to Ca^{2+} homeostasis and antioxidant systems in young grape plants. *Plan Sci, 170*, 685–694.

Wang, M., Xu, Q., Yu, J., & Yuan, M. (2010). The putative Arabidopsis zinc transporter ZTP29 is involved in the response to salt stress. *Plant Molecular Biology, 73*(4), 467–479.

Wang, S., Liang, D., Li, C., Hao, Y., Maa, F., & Shu, H. (2012). Influence of drought stress on the cellular ultrastructure and antioxidant system in leaves of drought tolerant and drought-sensitive apple rootstocks. *Plant Physiology and Biochemistry, 51*, 81–89.

Wang, W. X., Vinocur, B., & Altman, A. (2003). Plant responses to drought, salinity and extreme temperatures: Towards genetic engineering for stress tolerance. *Planta, 218*, 1–14.

Wang, X., & Mauzerall, D. L. (2004). Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment, 38*, 4383–4402.

Waraich, E. A., Ahmad, R., & Ashraf, M. Y. (2011a). Improving agricultural water use efficiency by nutrient management in crop plants. *Acta Agriculturae Scandinavica Section B—Soil and Plant Science, 61*, 291–304.

Waraich, E. A., Ahmad, R., & Saifullah. (2011b). Role of mineral nutrition in alleviation of drought stress in plants. *Australian Journal of Crop Science, 5*, 764–777.

Wiebbecke, C. F., Graham, M. A., Cianzio, S. R., & Palmer, R. G. (2012). Day temperature influences themale-sterile locus ms9 in soybean. *Crop Science, 52*, 1503–1510.

Wilkinson, S., Mills, G., Illidge, R., & Davies, W. J. (2012). How is ozone pollution reducing our food supply? *Journal of Experimental Botany, 63*, 527–536.

Wojtaszek, P. (1997). Oxidative burst: An early plant response to pathogen infection. *Biochemical Journal, 322*, 681–692.

Wu, F., & Zhang, G. (2002). Alleviation of cadmium-toxicity by application of zinc and ascorbic acid in barley. *Journal of Plant Nutrition, 25*, 2745–2761. doi:10.1081/PLN-120015536.

Xiaoqin, Y., Jianzhou, C., & Guangyin, W. (2009a). Effects of drought stress and selenium supply on growth and physiological characteristics of wheat seedlings. *Acta Physiologiae Plantarum, 31*, 1031–1036.

Xiaoqin, Y., Jianzhou, C., & Guangyin, W. (2009b). Effects of selenium on wheat seedlings under drought stress. *Biological Trace Element Research, 130*, 283–290.

Xue, Z. Y., DY, Z., Xue, G. P., Zhang, H., Zhao, Y. X., & Xia, G. M. (2004). Enhanced salt tolerance of transgenic wheat (*Tritivum aestivum* L.) expressing a vacuolar Na^+/H^+ antiporter gene with improved grain yields in saline soils in the field and a reduced level of leaf Na^+. *Plant Science, 167*, 849–859.

Yadav, S. K. (2010). Cold stress tolerance mechanisms in plants: A review. *Agronomy for Sustainable Development, 30*, 515–527.

Yamaguchi, T., & Blumwald, E. (2005). Developing salt-tolerant crop plants: Challenges and opportunities. *Trends in Plant Science, 10*(12), 615–620.

Yan, K., Chen, W., He, X., Zhang, G., Xu, S., & Wang, L. (2010). Responses of photosynthesis, lipid peroxidation and antioxidant system in leaves of *Quercus mongolica* to elevated O_3. *Environmental and Experimental Botany, 69*, 198–204.

Yao, X., Chu, J., & Ba, C. (2010). Responses of wheat roots to exogenous selenium supply under enhanced ultraviolet-B. *Biological Trace Element Research, 137*, 244–252.

Yao, X., Chu, J., & Wang, G. (2009). Effects of selenium on wheat seedlings under drought stress. *Biological Trace Element Research, 130*, 283–290.

Yildiztugay, E., Ozfidan-Konakci, C., Kucukoduk, M., & Tekis, S. A. (2016). The impact of selenium application on enzymatic and non-enzymatic antioxidant systems in *Zea mays* roots treated with combined osmotic and heat stress. *Archives of Agronomy and Soil Science*. doi:10.1080/03650340.2016.1201810.

Yordanova, R., & Popova, L. (2007). Effect of exogenous treatment with salicylic acid on photosynthetic activity and antioxidant capacity of chilled wheat plants. *General and Applied Plant Physiology, 33*, 155–170.

Yoshida, S. (1981). Physiological analysis of rice yield. In *Fundamentals of rice crop science* (pp. 231–251). Los Banos: International Rice Research Institute.

Yoshioka, M., Uchida, S., Mori, H., Komayama, K., Ohira, S., Morita, N., Nakanishi, T., & Yamamoto, Y. (2006). Quality control of photosystem II: Cleavage of reaction center D1 protein in spinach thylakoids by FtsH protease under moderate heat stress. *The Journal of Biological Chemistry, 281*, 21660–21669.

You, L., Rosegrant, M. W., Wood, S., & Sun, D. (2009). Impact of growing season temperature on wheat productivity in China. *Agricultural and Forest Meteorology, 149*, 1009–1014.

Yruela, I. (2005). Copper in plants. *Brazilian Journal of Plant Physiology, 17*, 145–256.

Yue, M., Li, Y., & Wang, X. (1998). Effects of enhanced ultraviolet-B radiation on plant nutrients and decomposition of spring wheat under field conditions. *Environmental and Experimental Botany, 40*, 187–196.

Zabihi-e-mahmoodabad, R., Jamaati-e-somarin, S., Khayatnezhad, M., & Gholamin, R. (2011). Effect of cold stress on germination and growth of wheat cultivars. *Advances in Environmental Biology, 5*, 94–97.

Zahedi, H., Noormohammadi, G., Rad, A. H. S., Habibi, D., & Boojar, M. M. A. (2009). Effect of zeolite and foliar application of selenium on growth, yield and yield component of three canola cultivar under conditions of late season drought stress. *Notulae Scientia Biologicae, 1*, 73–80.

Zeng, F. R., Zhao, F. S., Qiu, B. Y., Ouyang, Y. N., Wu, F. B., & Zhang, G. P. (2011). Alleviation of chromium toxicity by silicon addition in rice plants. *Agricultural Sciences in China, 10*, 1188–1196.

Zhang, B., Liu, W., Chang, S. X., & Anyia, A. O. (2010). Water deficit and high temperature affected water use efficiency and arabinoxylan concentration in spring wheat. *Journal of Cereal Science, 52*, 263–269.

Zhang, J. H., Huang, W. D., Liu, Y. P., & Pan, Q. H. (2005). Effects of temperature acclimation pretreatment on the ultrastructure of mesophyll cells in young grape plants (*Vitis vinifera* L. cv. Jingxiu) under cross-temperature stresses. *Journal of Integrative Plant Biology, 47*, 959–970.

Zhou, X., Yang, L., Qi, Y., Guo, P., & Chen, L. (2015). Mechanisms on boron-induced alleviation of aluminum-toxicity in *Citrus grandis* seedlings at a transcriptional level revealed by cDNA-AFLP analysis. *PloS One, 10*(3), e0115485. doi: 10.1371/journal.pone.0115485.

Zhu, J. K. (2007). Plant salt stress. In A. O'Daly (Ed.), *Encyclopedia of life sciences* (pp. 1–3). Chichester: Wiley.

Zlatev, Z., & Lidon, F. J. C. (2012). An overview on drought induced changes in plant growth, water relations and photosynthesis. *Emirates Journal of Food and Agriculture, 24*, 57–72.

Zlatev, Z. S., Lidon, F. J. C., & Kaimakanova, M. (2010). Plant physiological responses to UV-B radiation. *Emirates Journal of Food and Agriculture, 24*, 481–501.