Chapter 5
Abiotic Stress: Its Outcome and Tolerance in Plants

P. Rawat, D. Shankhdhar, and S. C. Shankhdhar

Abstract The onset of nineteenth century along with anthropogenic pressure paved the way for global climatic variation which is a major factor for global undernourishment, malnutrition and endangered food security. The major upshot of climate change is abiotic stress like salinity, flood and drought that declines the agricultural productivity. Abiotic stress hampers the survival of the plants and restricts their growth and development. Each abiotic stress confers negative impact on plants by altering its physiology, morphology and metabolism. Production of reactive oxygen species during stress condition alters the structure and metabolic function in plants and restricts its growth. Drought is one of the serious threats to crop productivity among the abiotic stress that imposes multidimensional effects on plants. Drought alters physiology and anatomy of the plants and is the main reason for economic loss in terms of livestock and grain yield in both developed and developing countries. Plants adapt several resistance mechanisms to cope up with the drastic impact of stress. Main tolerance mechanisms are alteration in membrane structure, escaping the unfavourable conditions, activation of antioxidant defense system, production of compatible solutes for maintaining osmotic balance of the cell. Present manuscript focuses on the outcome of major abiotic stress in plants and their tolerance strategies against the variable environmental conditions.

5.1 Introduction

Contemporary civilization and industrialization have led to global climate change whose consequences like flood, drought, high temperature and global warming are quite perceptible and hazardous for soil heath, microbial diversity and sustainable crop production. Climate fluctuation also threatens the vulnerable and endangered organisms in the ecosystem that are incompetent to endure such environmental changes in their habitat. Climate variability has immense impact on food security.

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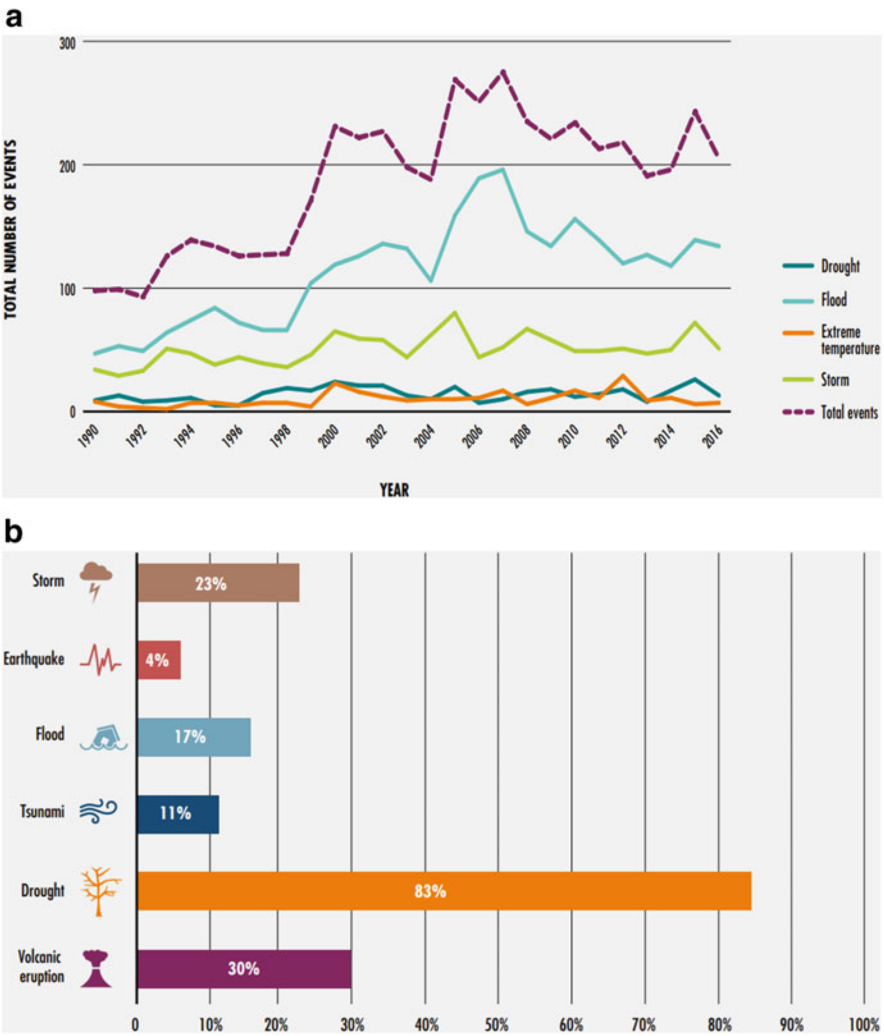

Fig. 5.1 (**a**) Rise in the calamitous events (1990–2016). Adopted from FAO (2018). (**b**) Damage and loss in agriculture as share of total damage and loss across all sectors by type of hazards. Adopted from FAO (2018)

It hits the underdeveloped regions of the world causing yield and economic losses. It has been estimated that 26% of total loss was in agriculture sector due to calamitous events from 2006 to 2016 (FAO 2018). Figure 5.1a, b illustrates the severity of disastrous events in the past years along with its impact on agricultural sector. There has been a dire inflation in the number of undernourished people across the world from 806 million in 2016 to 821 million in 2017 as an outcome of climate shock (FAO 2018). In view of the above facts, the foremost challenge is to provide food security to the projected global population of about 9.7 billion in 2050 under climate fluctuation and dwindling crop productivity.

Abiotic stress is an aftermath of climatologically variation that ceases plant growth, development and productivity below optimum levels. A surfeit or scant in energetic, chemical or physical condition in the nature paved the origin of abiotic stress in plants. The utmost abiotic stress comprises of drought, salinity, flooding and oxidative stress that abolishes metabolic equilibrium of plants thereby threatening food security (Fedoroff et al. 2010). Economic forfeiture in the developing countries in terms of crop and livestock production was discerned up to USD 96 billion from 2005 to 2015 with a 2.6% decrement in national agricultural value added growth due to occurrence of each climatic hazards (FAO 2018). An alarming upshot of climate shock is forecasted to decline agriculture productivity and influence five billion people by 2050 (UNESCO 2018; Watts 2018).

5.2 Abiotic Stress in Plants

5.2.1 *Salt Stress*

One of the most detrimental climate shocks is salinity stress which is prevalent in arid and semiarid regions in the world as depicted in Fig. 5.2. Approximately 33% of the world's irrigated land and 20% of overall cultivated land are devastated by salinity stress (Shrivastava and Kumar 2015). It has been forecasted that by 2050 around 50% of arable land would be influenced by salinity (Jamil et al. 2011). In India seven million hectares of land is sheathed by saline soil (Patel and Dave 2011). An electrical conductivity of precisely 4 dSm^{-1} of saturation extract from root zone at 25 °C marks the saline soil (Jamil et al. 2011). Salinity damages the agricultural productivity as the major food crops are susceptible to it. A remarkable yield loss of

Fig. 5.2 Salt affected regions of the world. Adopted from FAO (2016)

about 65% in wheat was evident as an outcome of salinity stress (Ahmad et al. 2013). Yield reduction of about 55% in corn and cotton was observed in case of salinity in the range of about 8–10 dSm^{-1} and 18 dSm^{-1}, respectively (Satir and Berberoglu 2016; Zörb et al. 2019).

5.2.2 *Impact of Salinity Stress in Plants*

Salinity stress devastates the plants by two ways: (a) Osmotic effect that diminishes plant potential for water uptake due to excess salt in soil and (b) ion excessive effect that occurs due to accumulation of excess salt in the leaf tissues (Greenway and Munns 1980). Salinity amends the major physiological processes like photosynthesis, transpiration, nutrient regulation and osmotic balance as an outcome and affects plant growth and yield. Influence of salinity stress in plants has been illustrated in Table 5.1.

Table 5.1 Outcome of salinity stress in plants

Parameters	Alterations	References
Germination	Hinders water imbibition by seeds	Khan and Gul (2006)
	Alters the enzyme activity requisite for metabolic functions	Gomes-Filho et al. (2008)
	Deteriorates seed coat, diminishes the seed vigour index and surges seed dormancy	Panuccio et al. (2014)
Water relation	Osmotic imbalance leading to soaring salt concentration near roots	Munns (2005)
	Decrement in relative water content and turgor pressure	Ghoulam et al. (2002)
Plant growth	Minimizes water retaining capacity of plant	Munns (2002b)
	Enhances ion toxicity that results in early leaves senescence	Munns (2002a, 2005)
Photosynthesis	Accumulation of Na^+ and Cl^- ions in chloroplasts	Sudhir and Murthy (2004)
	Alteration in electron transport chain by impeding photon phosphorylation and carbon metabolism	Farahbakhsh et al. (2017).
	Decrement in chlorophyll content	Saha et al. (2010)
	Modification in cytoplasmic structure, retardation in carboxylation reaction and generation of ROS	Maxwell and Johnson (2000)
Nutrient imbalance	High osmotic potential lessens nitrogen content in plants	Lea-Cox and Syvertsen (1993); Rozeff (1995); Bar et al. (1997)
	Low phosphorous content	Qadir and Schubert (2002)
	Reduced influx of Ca^{2+} and K^+ ions	Suhayda et al. (1990); Hu and Schmidhalter (1997); Asch et al. (2000)

5.2.3 Plant Tolerance Strategies against Salinity Stress

Resistance strategies of plants to salinity rely on environmental conditions and plant species. Plants mainly endure salt stress by three ways:

(a) Endurance to osmotic stress
(b) Efflux of sodium from leaf blades
(c) Tissue tolerance

5.2.3.1 Osmotic Stress Endurance

Osmotic stress is marked by generation of osmolytes like glycine betaine, proline, polyols, etc. to maintain the osmotic balance. Osmotic tolerance also aids in balancing stomatal conductance and leaf expansion during salinity (Rajendran et al. 2009). Osmolytes stabilize the membrane integrity, proteins and pigments in the cell and also alleviate reactive oxygen species (Krasensky and Jonak 2012; Gupta and Huang 2014). It was evident that proline accumulation improved the salinity tolerance in maize (Tang et al. 2019). Likewise, trehalose accumulation also assisted in boosting salinity endurance in wheat (Sadak 2019).

5.2.3.2 Sodium Ion Efflux from Leaf Blades

Outcome of salinity stress in plants comprises ion toxicity due to sodium ion (Na^+) accumulation inside the cell. This can be overcome by down regulating the expression of ionic channels and Na^+ transporters (Munns and Tester 2008; Rajendran et al. 2009). An antiporter (AtNHX1) confined in tonoplast of *Arabidopsis* maintains Na^+ balance in the cell under salinity condition by directing the influx of Na^+ ions from cytosol to vacuole (Apse et al. 1999). Likewise NAX1gene in durum wheat impedes Na^+ translocation in the shoots and leaf sheath from roots, whereas NAX2 gene confers high potassium ion (K^+)translocation in leaf (Flagella et al. 2006). Sodium exclusion theory for salt resistance has been validated in rice (Ren et al. 2005) and durum wheat (James et al. 2006). It was studied that potassium transporter *(*PpHKT1) gene from rootstock of almond also enhanced salt tolerance in transgenic *Arabidopsis* by balancing ion homeostasis (Kaundal et al. 2019).

5.2.3.3 Tissue Tolerance

For hindering the senescence of leaves and enhancing its survival rate, tissue tolerance is a salient attribute during stress. Generation of compatible solutes that balances the osmotic homeostasis in the cell and antioxidant defense system that scavenges the reactive oxygen species under stress condition is an attribute of tolerance of plants to stress condition (Hasegawa et al. 2000; Zhu 2001; Sakamoto and Murata 2002). Tissue resistance also incites the ion compartmentalization in the cell to diminish toxicity of ion (Munns and Tester 2008). A notable rise in osmolyte production like proline up to 14.87 μmol g^{-1} DW and an increment in antioxidants like ascorbate peroxidase up to 77%, catalase up to 15% and glutathione reductase up to 138% were recorded in chickpea as a tolerance response to salinity stress (Arefian et al. 2018).

5.3 Flooding Stress

Prolonged submergence and soil waterlogging result in hypoxic condition that constitutes flood stress in plants. One of the key limitations to crop productivity in high rainfall areas of the world is flood stress. Climate change promotes submergence to be more recurring and drastic (Pachauri et al. 2014). Approximately 10% of irrigated land in India, China, Russia and 16% of cultivable land in the USA are damaged by waterlogging (FAO 2015). Figure 5.3 explains the ubiquity of flood hazard in the world. According to statistical approximates of food and agriculture organization of United Nations, flood stress upshots 17% of total loss and damage in agriculture (FAO 2018).

It was discerned that annually 20–50% production loss in wheat occurred under waterlogging condition (Hossain and Uddin 2011). Overall 15% of maize production in South Asia is damaged by floods. India accounts for 25–30% maize production loss every year on account of flood stress (Bailey-Serres et al. 2012).

Fig. 5.3 Global flood hazard prevalence. Adopted from SEDAC (n.d.)

5.3.1 *Outcome of Flood Stress in Plants*

The prime consequence of flood stress in plant comprises anoxia or oxygen limitation. Necrosis, senescence, low nitrogen fixation and ultimately plant death are the consequences of flood stress (Hasanuzzaman et al. 2012). Overall effects of flood stress in plants are outlined in Table 5.2.

5.3.2 *Adaptation of Plants to Flood Stress*

5.3.2.1 Morphological Alterations

For escaping anoxic conditions under flood stress, plants showcase morphological adaptations. Submerged leaves have low stomatal counts and are often dissected and filamentous (Sculthorpe 1967). Vigorous adventitious root growth is one of the prominent adaptation as evident in *Sesbania javanica* (Jackson 2006) and *Chrysanthemum* (Yin et al. 2009). Decrement in root hairs and diameter, rapid shoot elongation are some of the evident variations (Jackson 2008). Under submergence, formation of leaf gas film improves carbohydrate supply, generation of adventitious roots and aeration of roots. In rice, resistance to radial oxygen loss is enhanced by

Table 5.2 Consequences of flood stress in plants

Parameters	Alterations	References
Anatomical variation	Over growth of aerenchyma, lenticels and adventitious roots	Ashraf (2009)
	Decrement in stele and seminal root diameter, reduced cortex thickness	Grzesiak et al. (1999)
	Increment in width of phloem tissue and number of xylem vessels	de Souza et al. (2013)
	Formation of suberized exodermis on root cortex periphery	Kulichikhin et al. (2014)
Physiology and metabolism	Impaired stomatal conductance, CO_2 assimilation	Ashraf (2009)
	Decrement in net photosynthetic rate, transpiration rate, PSII efficiency and rubisco activity	Zheng et al. (2009)
	Low relative water content and membrane stability	Kumar et al. (2013)
	Accumulation of hexose sugars in roots and organic acids in leaves	Vandoorne et al. (2014)
Nutrient availability	Enhanced nitrogen content and reduced phosphorous and potassium content in plant tissues	Reddy and mittra (1985)
	Reduced uptake of copper and zinc	Tarekegne et al. (2000)
Growth and yield	Reduction in leaf number, diameter, height and leaf area of plant, leaf epinasty	Parent et al. (2008); Gonzalez et al. (2009)
	Decline in dry matter accumulation, chlorosis, and flower abortion	Mensah et al. (2006)

development of effective barriers. This aids in shielding the plants from toxins generated from anoxic environment and boosts root tip aeration under flood stress (Kirk et al. 2014; Yamauchi et al. 2018).

5.3.2.2 Anatomical Alterations

To hinder the loss of radial oxygen from submerged roots, plants show formation of lateral diffusion barrier (Sauter 2013). Lenticels development is also evident in flood affected plants as this aids in oxygen diffusion in downward direction (Parelle et al. 2006). Aerenchyma formation is one of the unique characters of plants under flood or submerged condition as these gas spaces allow oxygen transport from roots to shoots (Shiono et al. 2008). Exodermis thickness was improved by 23.70% compared to control in *Garcinia brasiliensis* under flood state in addition to increment in root xylem vessels and phloem width (de Souza et al. 2013). In flood tolerant barley cultivar (TX9425 and Yerong), more well developed intercellular spaces in leaves and mesophyll cells were observed that enhanced photosynthesis due to quick gaseous exchange Zhang et al. 2016). In rice seedlings, rapid coleoptile elongation during germination is a marker for submergence tolerance that facilitates aeration of developing embryo (Guru and Dwivedi 2018).

5.3.2.3 Biochemical Alterations

Under flood stress, switch in the metabolism of plants from aerobic to anaerobic condition with high activity of alcohol dehydrogenase, a key enzyme in anaerobic fermentation is observed (Sairam et al. 2008). Proline content in *Casuarina* was high in tolerant cultivar as it acts as a signal molecule, an osmolyte and showcases antioxidant defense response under stress condition (Bajpai and Chandra 2015). Enhanced activity of alpha aminobutyric acid has been evident in soybean nodules in flooded conditions as this metabolite balances intercellular pH, acts as nitrogen reservoir under flood condition and also serves as antioxidant (Souza et al. 2016). Elevated activity of enzymes like phosphoenolpyruvate carboxylase, glutamate dehydrogenase and alcohol dehydrogenase was observed in flooded nodules of *Sesbania herbacea* (Krishnan et al. 2019).

5.4 Heavy Metal Stress

One of the major aftermaths of industrial revolution in the twenty-first century is heavy metal pollution in the environment. Heavy metals are potentially noxious elements and present in trace amount in soil. They are comprised of metalloids, lanthanoides and transition metals with atomic density ⍰6 g cm^{-3}except selenium, boron and arsenic (Park et al. 2011). The root cause of heavy metals in the environment encompasses usage of pesticides and fertilizers, combustion of fuels, mining, sewage sludge, oil spills, etc. Heavy metals are diverse in their functioning. Metals like iron, zinc, copper, nickel, manganese, chromium impart proper functioning of plant's metabolic processes contrarily lead, arsenic, mercury have negative effect on plant growth and productivity (Pierart et al. 2015). These noxious elements enter the food chain and attack human, animal and soil health (Augustsson et al. 2015).

Uptake of heavy metal by plants interrupts the chief metabolic processes like photosynthesis, nitrogen fixation and nutrients uptake and results in biomass and yield reduction and also death of the plants (Buendía-González et al. 2010). In China, about 20,000,000 acres of farmland is polluted by heavy metal with an annual crop loss of 1,000,000 million tons per year (Wu et al. 2010). About 12% of world's agricultural land is estimated to be affected by heavy metal pollution (Dziubanek et al. 2015). One of the most detrimental heavy metal for human health is lead. Lead exposure resulted in loss in economic productivity of about $977 billion annually in low to middle-income count (Attina and Trasande 2013). Statistical estimates of Institute for Health Metrics and Evaluation disclosed that lead exposure caused nearly 0.5 million deaths and 9.3 million life years lost among adults of 15 years and older (Landrigan et al. 2018).

5.4.1 Outcome of heavy metal stress in plants

Heavy metal stress deteriorates soil and plant health. Metal toxicity alters the morphology and physiology of plants at different growth stage as a consequence there is decline in crop productivity. Table 5.3 outlines the impact of heavy metal stress in plants.

5.4.2 Plant tolerance to heavy metal stress

5.4.2.1 Antioxidant enzymes

To escape heavy metal toxicity plants evolve many alterations. Exclusion of metal ions from the cell or binding with ligand prevents entry of metal ions to the roots is the first line of defense mechanism (Zeng et al. 2011). Metal ions also make complexes with carboxyl group of pectin in the cell wall thereby restricting its entry in the cell (Jiang and Liu 2010). Secondary response for metal detoxification is generation of antioxidant enzymes like superoxide dismutase, catalase and peroxidase. Compounds like glutathione, proline, cysteine, ascorbic acid also serve as scavengers of reactive oxygen species (Shahid et al. 2012; Pourrut et al. 2013).

Glutathione is a tripeptide antioxidant with thiol group and forms mercaptide bond with metals due to its nucleophilic thiol group and its reduced form also

Table 5.3 Out-turn of heavy metal stress in plants

Parameters	Modifications	References
Germination	Inhibition of water uptake by copper, cadmium	Kranner and Colville (2011)
	Reduction in germination percentage	Chigbo and Batty (2013)
	Formation of abnormal embryos and decrement in seed viability	Stvolinskaya (2000)
	Slow activity of alpha amylases, phosphatases. Decrement in remobilization of storage reserves	Kalai et al. (2014)
	Lipid peroxidation and proline accumulation in the radical	Kalai et al. (2014)
Plant growth	Chlorosis, decline in growth and yield, reduced nutrient uptake and nitrogen fixing potential	Guala et al. (2010)
	Generation of reactive oxygen species	Romero-Puertas et al. (2004)
Photosynthesis	Disruption in energy transfer in light harvesting complex, decline in chlorophyll and carotenoid content	Kuzminov et al. (2013)
	Electron transport inhibition between photosystem I and II	Rama Devi and Prasad (1999)
	Deformation of chloroplast ultrastructure	Kalaji and Loboda (2007)
Nutrient uptake	Low concentration of zinc, iron, calcium and manganese	Chatterjee et al. (2004)
	Decline in shoot nitrate content and nitrate reductase activity	Xiong et al. (2006)

scavenges peroxide radicals. Glutathione conjugates with compounds of heavy metals that are translocated to vacuole to protect cell from its harmful effects (Klein et al. 2006; Yazaki 2006). It was also studied that in response to cadmium toxicity there is a modulation in the activity of antioxidants like guaiacol peroxidase, ascorbate peroxidase and catalase in tolerant plants (Alves et al. 2017; Borges et al. 2018). In *Brassica juncea* L. such kind of high efficiency antioxidative defense system was evident during caesium toxicity (Lai and Luo 2019).

5.4.2.2 Metallothioneins and Phytochelatins

Vacuolar sequestration of heavy metals is an important response of plants to metal stress. Complex formation of metal ion with ligand reduces the toxicity of heavy metals. Metallothioneins and phytochelatins rich in cysteine are natural metal chelators in plants that reduce metal toxicity by forming mercaptide bonds with metals and sequester them to vacuoles (Gupta et al. 2010; Jiang and Liu 2010)**.** In *Brassica napus,* cadmium toxicity results in strong expression of MT4 metallothionein in germinating seeds as a defense mechanism (Mierek-Adamska et al. 2018). Likewise in *Oryza sativa,* phytochelatin synthase genes (OsPCS5 and OsPCS15) were profoundly induced under cadmium stress as tolerance mechanism.

These genes encode phytochelatins that bind heavy metals in cytosol and detoxify them in the vacuoles (Park et al. 2019).

5.5 Low Temperature Stress

Chilling or low temperature stress amends the plant morphology, physiology and metabolism. Occurrence of chilling stress at temperature 0 °C to 15 °C whereas freezing stress at ambient temperature for ice crystal formation causes cellular injury and osmotic dehydration in the cell (Bhatla 2018).

5.5.1 Impact of low temperature stress in plants

Chilling in plants is advantageous for breaking seed dormancy, for vernalization and cold acclimation. In contrast, chilling in susceptible crops has many aftermaths as listed in Table 5.4.

5.5.2 Adaptations to low temperature stress

5.5.2.1 Cold acclimation

Increment in phospholipid proportion and decrement in ceramide and sugar containing lipids in plasma membrane results in reduction in expansion induced lysis. Expression of sugar producing enzymes like acid invertase, galactinol synthase and sucrose synthase to improve membrane stability is induced in response to cold acclimation (Turhan and Ergin 2012). Accumulation of compatible solutes like

Table 5.4 Consequences of chilling stress in susceptible crops

Parameters	Modifications	References
Lipid membrane	Membrane becomes leaky and dysfunctional	Bhatla (2018)
	Membrane transport and receptors disabled	
	Cellular structure distorted	
	Osmotic dehydration of cell	
Photosynthetic apparatus	Impaired electron transport chain	Bhatla (2018); Wise et al. (1987)
	Generation of reactive oxygen species	
	Cell plasmolysis	
	Chloroplast swelling and dilation of thylakoids, disintegration of chloroplast	
	Depletion of starch and phosphorylated metabolites in cell	

hydroxyl proline and arabinose in the cell maintains osmotic balance during cold acclimation (Bhatla 2018). Expression of hydrophilic and LEA (late embryogenesis abundance protein) proteins declines the denaturation of proteins under cold and drought stress. In *Brassica napus,* dehydrin proteins, a class of LEA proteins was highly expressed under cold stress in tolerant cultivar. It is used as biomarker for selection of cold tolerant lines (Maryan et al. 2019).

5.5.2.2 Modification in gene expression

Expression of cold regulated genes (COR) confers cold tolerance in plants by stabilizing the plasma membrane during low temperature stress. Hydrophilic proteins encoded by COR genes expressed during low temperature stress are involved in the production of anthocyanin and play indirect role in cold acclimatization. Extracellular production of antifreeze proteins (AFP) prevents ice crystal formation during low temperature stress. Molecular chaperons like HSP90 restrict denaturation of proteins during chilling stress. Other proteins like MAP (mitogen activated protein) kinase and calmodulin related proteins are encoded by COR genes and impart role in cold temperature signalling in plants (Bhatla 2018). A chromatin remodelling factor PICKLE (PKL) was found responsible for cold stress tolerance in *Arabidopsis*. It also modulates expression of other cold responsive genes like RD29A and COR15A (Zhao et al. 2019). In *Brassica rapa* L., genes such as temperature-induced lipocalin-1, zinc finger protein ZAT12, dehydrin ERD10 and adenosylhomocysteinase 2 were analysed and found to be involved in cold stress tolerance (Ma et al. 2019).

5.6 Drought Stress

One of the most disastrous outcomes of climate change is drought that restricts plant growth and development in both developed and developing countries. The utmost driver of undernourishment and hunger is geographical and global drought that declines agricultural productivity (FAO 2017).US, a technologically advanced country encounters an annual loss of $ 6 billion in agricultural productivity due to drought and such losses are more severe in underdeveloped and developing countries (CIA 2017). Around 20% of world's cultivable land is hit by drought and more than 80% damage in livestock and agricultural production is because of drought stress (FAO 2018). Major drought exposed regions in the world have been delineated in Fig. 5.4.

Drought is a climatic variation with perpetuate periods of rainfall scarcity that results in hunger, malnutrition, deficit food productivity and ultimately food insecurity. Plants encounter severe drought when water loss via transpiration is high enough or when roots are deficient in water supply (Anjum et al. 2011). A severe drought can threaten the national food availability and results in pervasiveness of undernourishment**.** Approximate global yield loss of 21% in wheat and 40% in

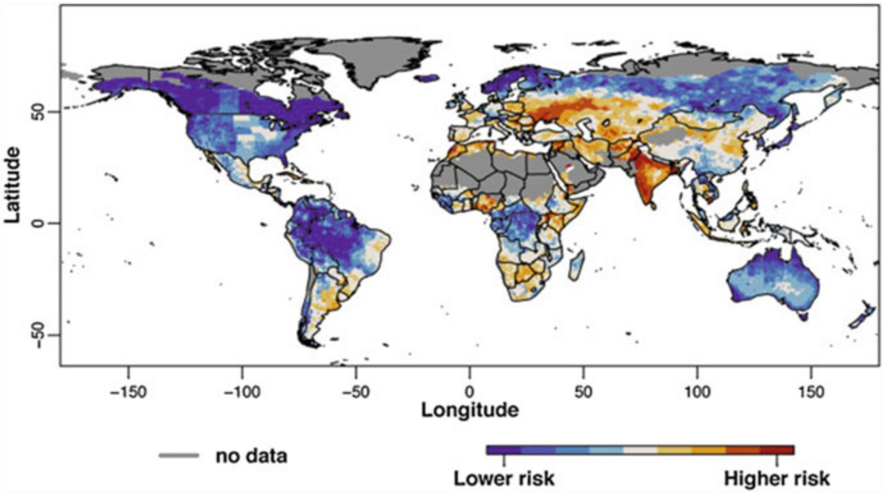

Fig. 5.4 Global map of drought affected regions. Adapted from Carrao et al. (2016)

maize was observed from 1980 to 2015 (Daryanto et al. 2016). Table 5.5 illustrates susceptible and resistant crops under major abiotic stress.

Drought alters photosynthesis, water balance, nutrient acquisition, oxidative metabolism and assimilates partitioning in plants. This modification in plants depends on species, growth stage of the plants and environmental conditions. Apparent symptoms of drought in plants are depicted in Fig. 5.5. Reduction in grain filling rate, harvest index and solar use efficiency are some key drivers responsible for diminished yield under drought stress. Table 5.6 describes deleterious impact of drought stress in plants ranging from morphological, biochemical to molecular level and is discernible at every phenological stage of crop growth at any period of time (Farooq et al. 2009; Deepak et al. 2019).

5.6.1 *Outcome of Drought Stress on Morphological Attributes*

The foremost impact of drought stress on morphology of plant is restricted seed germination and seedling growth (Farooq et al. 2009). Drought negatively alters seed vigour, seedling growth and also results in poor seed quality as reported in *Medicago sativa* (Zhang et al. 2019a, b), *Oryza sativa* (Bhavyasree et al. 2019), *Glycine max* (Reddy et al. 2019), *Zea mays* and *Sorghum* (Queiroz et al. 2019).

Drought impedes mitosis and cell enlargement because of restricted water flow from xylem to neighbouring cells (Hussain et al. 2008). Reduction in plant size and biomass is one of the major morphological alterations in plants during drought stress. Fifty percent reduction in biomass in wheat was observed as compared to control

Table 5.5 Comparative representation of crops for resistance and tolerance to different abiotic stress

Stress	Sensitive crop	Reference	Resistant crop	Reference
Salinity	*Brassica napus* L.	Dolatabadi et al. (2019)	*Hordeum vulgare*	Han et al. (2018)
	Phaseolus vulgaris	Lahaye and Epstein (1971)	*Echinochloa frumentaceae*	Williams et al. (2019)
	Oryza sativa L.	Khatun et al. (1995)	*Beta vulgaris* L.	Wu et al. (2018)
	Triticum aestivum	Ahmad et al. (2013)	*Vigna unguiculata*	Pan et al. (2019)
	Lupinus albus	Jeschke (1984)	*Solanum lycopersicum*	Amjad et al. (2019)
Flood	*Zea mays*	Panozzo et al. (2019)	*Saccharum officinarum*	Singh et al. (2019)
	Solanum lycopersicum	Ezin et al. (2010)	*Oryza sativa* L.	Dwivedi et al. (2018)
	Glycine max	Tewari et al. (2016)	*Solanum dulcamara* L.	Dawood et al. (2014)
	Triticum aestivum	Zhou (2010)	*Zea nicaraguensis*	Yamauchi et al. (2018)
	Cicer arietinum	Solaiman et al. (2007)	*Populus euphratica*	Yu et al. (2015)
Heavy metal	*Triticum aestivum* (Lead)	Alamri et al. (2018)	*Lupinus* (Cadmium, nickel)	Rathaur et al. (2012)
	Oryza sativa L. (Cadmium, arsenic)	Makino et al. (2019)	*Brassica napus* (Nickel, cadmium, copper)	Marchiol et al. (2004)
	Lolium perenne L. (Aluminium)	Parra-Almuna et al. (2018)	*Raphanus sativus* (Nickel, cadmium, copper)	Marchiol et al. (2004)
	Brassica juncea (Copper)	Yadav et al. (2018)	*Setaria italica L.* (Cadmium)	Chiang et al. (2011)
	Solanum lycopersicum (Cadmium)	Carvalho et al. (2018)	*Miscanthus sinensis* (Aluminium)	Ezaki et al. (2008)
Chilling	*Solanum lycopersicum*	Ronga et al. (2018)	*Arabidopsis thaliana*	Schulz et al. (2016)
	Zea mays	Bilska-Kos et al. (2017)	*Brassica juncea* L.	Sinha et al. (2015)
	Cicer arietinum	Selpair (2018)	*Mentha arvensis*	Dhawan et al. (2018)
	Brassica oleracea	Zhang et al. (2019a, b)	*Pisum sativa* L.	Zhang et al. (2016)
	Vigna radiata	Batra et al. (2018)	*Capsicum annuum*	Shawon et al. (2017)
Drought	*Oryza sativa* L.	Lawas et al. (2018)	*Setaria italica*	Han et al. (2019)

(continued)

Table 5.5 (continued)

Stress	Sensitive crop	Reference	Resistant crop	Reference
	Triticum aestivum	Bakhshandeh et al. (2019)	*Sorghum*	Ohnishi et al. (2019)
	Zea mays	Daryanto et al. (2016)	*Arachis hypogaea* L.	Banavath et al. (2018)
	Cicer arietinum	Kaloki et al. (2019)	*Macrotyloma uniflorum*	Sharma et al. (2018)
	Glycine max	Popović et al. (2015)	*Brassica napus* L.	Mahmood et al. (2019)
	Helianthus annuus	Pekcan et al. (2015)	*Hordeum vulgare*	Carter et al. (2019)

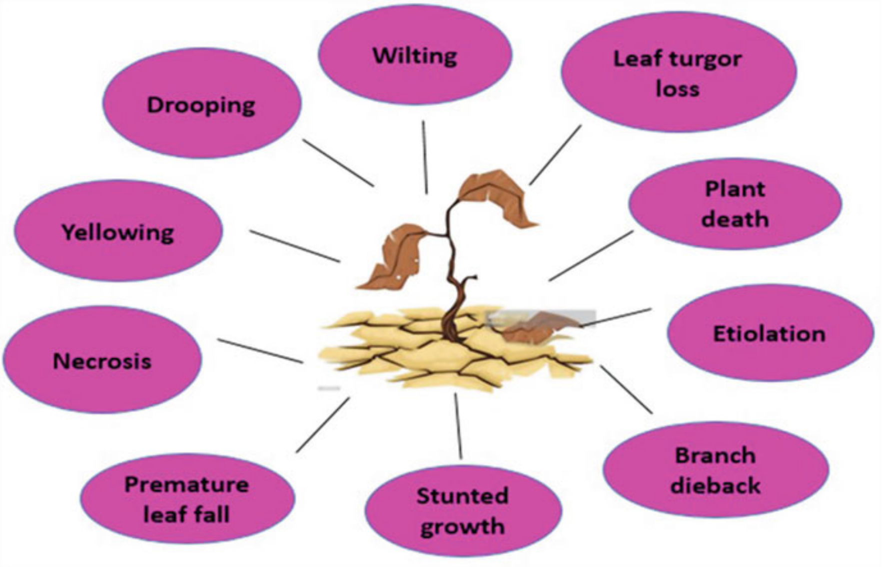

Fig. 5.5 Drought stress prodrome in plants

under drought stress (Paul et al. 2019). Dry weight and fresh weight of root and shoot as well as root shoot ratio tend to cut down in drought induced *Brassica napus* L. (Khan et al. 2019).

Decrement in stomatal aperture, leaf rolling, cutinization of leaf surfaces are some observable drought stress induced morphological parameters (Hussain et al. 2008). Drought hampers the leaf size, grain yield in crops, for instance, yield parameters like panicle length, seed setting rate and grain weight declined in *Oryza sativa* L. under drought (Wei et al. 2017). Likewise in wheat, 62% of grain loss was observed in drought condition compared to well-watered conditions (Paul et al. 2019).

Table 5.6 Salient modifications in drought stricken plants

Parameters	Modification	Reference
Morphology	Inhibition of seed germination	Farooq et al. (2009)
	Reduce shoot and root dry weight	Manickavelu et al. (2006)
	Diminished leaf area and number of stomata	Jaleel et al. (2009)
	Impaired mitosis and cell elongation	Hussain et al. (2008)
	Loss of turgor pressure and cell growth	Taiz and Zeiger (2006)
Water and nutrient relation	Low water use efficiency and transpiration rate	Turner et al. (2001)
	Low uptake of phosphorous, calcium and magnesium	Barber (1995)
	Enhanced nitrogen uptake	Barber (1995)
Photosynthesis	Reduction in RUBP generation and photosystem II activity	Wise et al. (2004); Camejo et al. (2006)
	Low chlorophyll content	Din et al. (2011)
Assimilate partitioning	Decline in translocation of assimilates from source to sink	Kim et al. (2000)
	Disturbance in phloem loading and unloading	Zinselmeier et al. (1999)
	Low potential of sink to utilize the assimilates	Zinselmeier et al. (1999)

5.6.2 Physiological and Biochemical Alterations Under Drought

Physiological attributes like transpiration rate, stomatal conduction, leaf water potential and relative water content are adversely affected by drought. Low water potential, transpiration rate, relative water content and enhanced leaf temperature were observed in *Oryza sativa* under drought (Fahad et al. 2017). Drought stress induces the formation of reactive oxygen species (ROS) along with enhanced generation of osmolytes like proline, glycine betaine. Production of ROS leads to oxidative stress that ultimately results in cell death in plants (Silva et al. 2019).

Another important trait influenced by drought is photosynthesis. Drought stress induces reduction in leaf expansion, damages the photosynthetic apparatus and activity of photosynthetic enzymes. Reduction in phosphorylation and disruption in ATP synthesis are key drivers for impaired photosynthesis under drought (Fahad et al. 2017). Reduction in thylakoid membrane proteins and PSII activity under PEG induced drought stress have been evident in many studies (Wang et al. 2019).

Activity of rubisco, a motor enzyme of photosynthesis is declined drastically under drought. Reduction in amount of substrate, i.e. ribulose 1, 5 bisphosphate for carboxylation, modification in ultrastructure of rubisco and chloroplast and acidification of chloroplast stroma are the driving factors for decrement in rubisco activity. Other enzymes like fructose-1, 6-bisphosphatase, NADP-glyceraldehyde phosphate dehydrogenase, phosphoribulokinase, phosphoenol pyruvate carboxylase and pyruvate orthophosphate dikinase also decline under drought stress (Farooq et al. 2009).

Drought restricts nutrient movement from soil to plants. Under drought, root growth and proliferation are hindered that limit nutrient translocation in plants. Limited flow of oxygen, carbon and nitrogen assimilation in root nodules impedes nitrogen fixing ability of legumes under drought (Ladrera et al. 2007). Nitrate reduction in leaves was limited by declined photosynthesis, which supplies reducing power, generated during photosynthetic via electron transport for the process of nitrate reduction (Chen et al. 2018).

5.6.3 Adaptation of Plants to Drought Stress

5.6.3.1 Escape

Drought escape is characterized by short life cycle that enables plants to flower early before onset of drought. Growing season is dependent on environmental variation and plant genotype. Drought escape is enhanced when development of plant synergizes with duration when soil moisture is available. Although drought escape helps in plants survival during stress yet there is a decrement in the yield (Farooq et al. 2009). High grain yield in *Lens culinaris* was recorded under early drought as a result of drought escape. Maximum leaf area, stomatal conductance, high stomatal density, early flowering with short life cycle were also observed as an outcome of drought escape strategy in lentil (Sanchez-Gomez et al. 2019).

5.6.3.2 Avoidance

Avoidance is marked by maintaining the water potential of plants during drought. It is also characterized by reduced water deprivation through transpiration and balancing the water uptake from soil. For efficient water uptake, a deep and extensive root system is required along with thick cuticle whose formation requires high input of energy that ultimately results in low yield. Therefore, plants with avoidance strategies are generally of compact size (Lisar et al. 2012). In *Sorghum,* aquaporin genes PIP2;3 were strongly expressed in roots under drought compared to roots under watered conditions. Aquaporins are the membrane proteins that allow water and solute passage through the membrane into cell and their expression under drought is an adaptive strategy (Schulze et al. 2019).

5.6.3.3 Tolerance

Tolerance to drought stress is perceptible by limited area and number of leaves during water deficit condition. Plants show traits like formation of trichomes and hairy leaves which reduce leaf temperature during drought. Root architecture like root density, root proliferation, root growth rate are some key alterations in plants during drought. Reduction in stomata number, increment in root shoot ratio, accumulation of osmolytes and induction of antioxidant defense system are other drought tolerance traits in plants (Sapeta et al. 2013). In sorghum, leaf rolling, leaf waxiness, stay green trait, root architecture, abscisic acid metabolism, ion transporter, transpiration efficiency and osmotic adjustments are drought tolerant traits that enable it to survive under drought stress (Badigannavar et al. 2018).

5.7 Conclusion

Major constraint for sustainable agricultural productivity and global food security is abiotic stress which is an outcome of global climate change. Extreme weather conditions attack morphological, physiological and biochemical attributes of the plants and threat their survival in the environment. Multiple abiotic stresses like salinity, flood, heavy metal and drought impact the crop yield. Drought is the most devastating abiotic stress that declines the global crop productivity. Drought hampers seed germination, reduces the stomatal frequency and diminishes leaf area and water potential. At physiological level, drought restricts photosynthesis, thylakoid structure and enzyme production. All these modifications alter the metabolism and limit growth and development of plants. Despite such abiotic constraints, plants have inherent tolerance mechanisms that enable them to cope up and survive under extreme conditions. Activation of antioxidant defense system, changes in the membrane lipid composition and enzyme production as well as morphological alterations in plants are some of the tolerance traits in plants. In spite of such adaptive strategies, improvements in the tolerance of plants against the extreme calamities are required. Strategies like alteration in expression of stress responsive genes and transcription factors are potential candidates to develop stress tolerant crops. More emphases should be there on molecular research for exploiting the stress tolerance traits and minimizing the aftermath of stress in plants.

References

Ahmad M, Shahzad A, Iqbal M, Asif M, Hirani AH (2013) Morphological and molecular genetic variation in wheat for salinity tolerance at germination and early seedling stage. Aust J Crop Sci 7:66–74

Alamri SA, Siddiqui MH, Al-Khaishany MY, Nasir Khan M, Ali HM, Alaraidh IA, Alsahli AA, Al-Rabiah H, Mateen M (2018) Ascorbic acid improves the tolerance of wheat plants to lead toxicity. J Plant Interact 13:409–419

Alves LR, Monteiro CC, Carvalho RF, Ribeiro PC, Tezotto T, Azevedo RA, Gratão PL (2017) Cadmium stress related to root-to-shoot communication depends on ethylene and auxin in tomato plants. Environ Exp Bot 134:102–115

Amjad M, Ameen N, Murtaza B, Imran M, Shahid M, Abbas G, Naeem MA, Jacobsen SE (2019) Comparative physiological and biochemical evaluation of salt and nickel tolerance mechanisms in two contrasting tomato genotypes. Physiol Plant 168:27–37

Anjum SA, Wang LC, Farooq M, Hussain M, Xue LL, Zou CM (2011) Brassinolide application improves the drought tolerance in maize through modulation of enzymatic antioxidants and leaf gas exchange. J Agron Crop Sci 197:177–185

Apse MP, Aharon GS, Snedden WA, Blumwald E (1999) Salt tolerance conferred by overexpression of a vacuolar Na+/H+ antiport in Arabidopsis. Science 285:1256–1258

Arefian M, Vessal S, Shafaroudi SM, Bagheri A (2018) Comparative analysis of the reaction to salinity of different chickpea (Cicer aretinum L.) genotypes: a biochemical, enzymatic and transcriptional study. J. Plant Growth Regul 37:391–402

Asch F, Dingkuhn M, Dörffling K, Miezan K (2000) Leaf K/Na ratio predicts salinity induced yield loss in irrigated rice. Euphytica 113:109–118

Ashraf M (2009) Biotechnological approach of improving plant salt tolerance using antioxidants as markers. Biotechnol Adv 27:84–93

Attina TM, Trasande L (2013) Economic costs of childhood lead exposure in low-and middle-income countries. Environ Health Perspect 121:1097–1102

Augustsson AL, Uddh-Söderberg TE, Hogmalm KJ, Filipsson ME (2015) Metal uptake by homegrown vegetables–the relative importance in human health risk assessments at contaminated sites. Environ Res 138:181–190

Badigannavar A, Teme N, de Oliveira AC, Li G, Vaksmann M, Viana VE, Ganapathi TR, Sarsu F (2018) Physiological, genetic and molecular basis of drought resilience in sorghum [Sorghum bicolor (L.) Moench]. Indian J Plant Physiol 23(4):670–688

Bailey-Serres J, Lee SC, Brinton E (2012) Waterproofing crops: effective flooding survival strategies. Plant Physiol 160:1698–1709

Bajpai S, Chandra R (2015) Effect of waterlogging stress on growth characteristics and sod gene expression in sugarcane. Int J Sci Res Publ 5:1–8

Bakhshandeh S, Corneo PE, Yin L, Dijkstra FA (2019) Drought and heat stress reduce yield and alter carbon rhizodeposition of different wheat genotypes. J Agron Crop Sci 205:157–167

Banavath JN, Chakradhar T, Pandit V, Konduru S, Guduru KK, Akila CS, Podha S, Puli CO (2018) Stress inducible overexpression of AtHDG11 leads to improved drought and salt stress tolerance in peanut (*Arachis hypogaea* L.). Front Chem 6:1–24

Bar Y, Apelbaum A, Kafkafi U, Goren R (1997) Relationship between chloride and nitrate and its effect on growth and mineral composition of avocado and citrus plants. J Plant Nutr 20:715–731

Barber SA (1995) Soil nutrient bioavailability: a mechanistic approach, 2nd edn. New York, Wiley

Batra NG, Kumari N, Sharma V (2018) Chlorophyll fluorescence based assessment of low temperature stress in different varieties of *Vigna radiata* (L.). Int J Plant Res 31:146–155

Bhatla SC (2018) Abiotic stress. In: Plant physiology, development and metabolism. Springer, Singapore, pp 969–1028

Bhavyasree RK, Joel AJ, Jeyaprakash P, Raveendran M (2019) The effect of induced drought stress on seedling vigour and antioxidant enzymes in wild and cultivated Oryza species. Int J Chem Stud 7:1078–1081

Bilska-Kos A, Solecka D, Dziewulska A, Ochodzki P, Jończyk M, Bilski H, Sowiński P (2017) Low temperature caused modifications in the arrangement of cell wall pectins due to changes of osmotic potential of cells of maize leaves (*Zea mays* L.). Protoplasma 254:713–724

Borges KLR, Salvato F, Alcântara BK, Nalin RS, Piotto FA, Azevedo RA (2018) Temporal dynamic responses of roots in contrasting tomato genotypes to cadmium tolerance. Ecotoxicology 27:245–258

Buendía-González L, Orozco-Villafuerte J, Cruz-Sosa F, Barrera-Díaz CE, Vernon-Carter EJ (2010) Prosopis laevigata a potential chromium (VI) and cadmium (II) hyperaccumulator desert plant. Bioresour Technol 101:5862–5867

Camejo D, Jiménez A, Alarcón JJ, Torres W, Gómez JM, Sevilla F (2006) Changes in photosynthetic parameters and antioxidant activities following heat-shock treatment in tomato plants. Funct Plant Biol 33:177–187

Carrao H, Naumann G, Barbosa P (2016) Mapping global patterns of drought risk: an empirical framework based on sub-national estimates of hazard, exposure and vulnerability. Glob Environ Chang 39:108–124

Carter AY, Ottman MJ, Curlango-Rivera G, Huskey DA, D'Agostini BA, Hawes MC (2019) Drought-tolerant barley: II. Root tip characteristics in emerging roots. Agronomy 9:1–10

Carvalho MEA, Piotto FA, Franco MR, Borges KLR, Gaziola SA, Castro PRC, Azevedo RA (2018) Cadmium toxicity degree on tomato development is associated with disbalances in B and Mn status at early stages of plant exposure. Ecotoxicology 27:1293–1302

Chatterjee C, Dube BK, Sinha P, Srivastava P (2004) Detrimental effects of lead phytotoxicity on growth, yield, and metabolism of rice. Commun Soil Sci Plant Anal 35:255–265

Chen H, Zhang Q, Lu Z, Xu F (2018) Accumulation of ammonium and reactive oxygen mediated drought-induced rice growth inhibition by disturbed nitrogen metabolism and photosynthesis. Plant Soil 431:107–117

Chiang PN, Chiu CY, Wang MK, Chen BT (2011) Low-molecular-weight organic acids exuded by Millet (*Setaria italica* (L.) Beauv.) roots and their effect on the remediation of cadmium-contaminated soil. Soil Sci 176:33–38

Chigbo C, Batty L (2013) Effect of combined pollution of chromium and benzo (a) pyrene on seed growth of *Lolium perenne*. Chemosphere 90:164–169

CIA (2017) The world factbook. https://www.cia.gov/library/publications/the-world-factbook/. Accessed 23 Sept 2019

Daryanto S, Wang L, Jacinthe PA (2016) Global synthesis of drought effects on maize and wheat production. PLoS One 11:1–15

Dawood T, Rieu I, Wolters-Arts M, Derksen EB, Mariani C, Visser EJ (2014) Rapid flooding-induced adventitious root development from preformed primordia in *Solanum dulcamara*. AoB Plants 6:1–13

Deepak SB, Thakur A, Singh S, Bakshi M, Bansal S (2019) Changes in crop physiology under drought stress: a review. J Pharmacogn Phytochem 8:1251–1253

de Souza TC, dos Santos SE, Dousseau S, de Castro EM, Magalhães PC (2013) Seedlings of *Garcinia brasiliensis* (Clusiaceae) subjected to root flooding: physiological, morphoanatomical, and antioxidant responses to the stress. Aquat Bot 111:43–49

Devi SR, Prasad MNV (1999) Membrane lipid alterations in heavy metal exposed plants. In: Prasad MNV (ed) Heavy metal stress in plants. Springer, Berlin, Heidelberg, pp 99–116

Dhawan SS, Mishra A, Gupta P, Bahl JR, Bansal RP (2018) Phylogentic relationship of cold tolerant Mentha arvensis variety 'CIM Kranti' with some released varieties as assessed through physiological and molecular analysis. J Appl Res Med Aromat Plants 10:67–74

Din J, Khan SU, Ali I, Gurmani AR (2011) Physiological and agronomic response of canola varieties to drought stress. J Anim Plant Sci 21:78–82

Dolatabadi N, Toorchi M, Valizadeh M, Bandehagh A (2019) The proteome response of salt-sensitive rapeseed (Brassica napus L.) genotype to salt stress. Not Bot Horti Agrobot Cluj Napoca 47:17–23

Dwivedi SK, Kumar S, Bhakta N, Srivastava AK, Mishra JS, Kumar V, Kumara BH, Bhatt BP, Singh S (2018) Physiological mechanism and nutrient management strategies for flood tolerance in rice grown in lowland flood prone ecosystem. J Crop Sci Biotechnol 21:321–331

Dziubanek G, Piekut A, Rusin M, Baranowska R, Hajok I (2015) Contamination of food crops grown on soils with elevated heavy metals content. Ecotoxicol Environ Saf 118:183–189

Ezaki B, Nagao E, Yamamoto Y, Nakashima S, Enomoto T (2008) Wild plants, *Andropogon virginicus* L. and *Miscanthus sinensis* Anders, are tolerant to multiple stresses including aluminum, heavy metals and oxidative stresses. Plant Cell Rep 27:951–961

Ezin V, Pena RDL, Ahanchede A (2010) Flooding tolerance of tomato genotypes during vegetative and reproductive stages. Braz J Plant Physiol 22:131–142

Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, Sadia S, Nasim W, Adkins S, Saud S, Ihsan MZ (2017) Crop production under drought and heat stress: plant responses and management options. Front Plant Sci 8:1–16

FAO (2015) Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a-bc600e.pdf. Accessed 1 Oct 2016

FAO (2016) Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a-i6471e.pdf. Accessed 1 Oct 2017

FAO (2017) How close we are to zero Hunger. http://www.fao.org/state-of-food-securitynutrition/en/geos/kz.html. Accessed 1 Mar 2019

FAO (2018) The state of food security and nutrition in the world. http://www.fao.org/state-of-food-security-nutrition/en/. Accessed 15 Sept 2019

Farahbakhsh H, Pasandi Pour A, Reiahi N (2017) Physiological response of henna (*Lawsonia inermise* L.) to salicylic acid and salinity. Plant Prod Sci 20:237–247

Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA (2009) Plant drought stress: effects, mechanisms and management. In: Lichtfouse E, Navarrete M, Debaeke P, Véronique S, Alberola C (eds) Sustainable agriculture. Springer, Dordrecht, pp 153–188

Fedoroff NV, Battisti DS, Beachy RN, Cooper PJ, Fischhoff DA, Hodges CN, Knauf VC, Lobell D, Mazur BJ, Molden D, Reynolds MP (2010) Radically rethinking agriculture for the 21st century. Science 327:833–834

Flagella Z, Trono D, Pompa M, Di Fonzo N, Pastore D (2006) Seawater stress applied at germination affects mitochondrial function in durum wheat (*Triticum durum*) early seedlings. Funct Plant Biol 33:357–366

Ghoulam C, Foursy A, Fares K (2002) Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. Environ Exp Bot 47:39–50

Gomes-Filho E, Lima CRFM, Costa JH, da Silva ACM, Lima MDGS, de Lacerda CF, Prisco JT (2008) Cowpea ribonuclease: properties and effect of NaCl-salinity on its activation during seed germination and seedling establishment. Plant Cell Rep 27:147–157

Gonzalez JA, Gallardo M, Hilal M, Rosa M, Prado FE (2009) Physiological responses of quinoa (*Chenopodium quinoa* Willd.) to drought and waterlogging stresses: dry matter partitioning. Bot Stud 50:35–42

Greenway H, Munns R (1980) Mechanisms of salt tolerance in nonhalophytes. Annu Rev Plant Physiol 31:149–190

Grzesiak S, Hura T, Grzesiak MT, Pieńkowski S (1999) The impact of limited soil moisture and waterlogging stress conditions on morphological and anatomical root traits in maize (*Zea mays* L.) hybrids of different drought tolerance. Acta Physiol Plant 21:305–315

Guala SD, Vega FA, Covelo EF (2010) The dynamics of heavy metals in plant–soil interactions. Ecol Model 221:1148–1152

Gupta B, Huang B (2014) Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. Int J Genom 2014:1–18

Gupta DK, Huang HG, Yang XE, Razafindrabe BHN, Inouhe M (2010) The detoxification of lead in Sedum alfredii H. is not related to phytochelatins but the glutathione. J Hazard Mater 177:437–444

Guru A, Dwivedi P (2018) Physiological, biochemical and molecular mechanism of submergence tolerance in rice (*Oryza sativa* L.). J Pharmacogn Phytochem 7:1116–1121

Han Y, Yin S, Huang L, Wu X, Zeng J, Liu X, Qiu L, Munns R, Chen ZH, Zhang G (2018) A sodium transporter HvHKT1; 1 confers salt tolerance in barley via regulating tissue and cell ion homeostasis. Plant Cell Physiol 59:1976–1989

Han Y, Yang H, Wu M, Yi H (2019) Enhanced drought tolerance of foxtail millet seedlings by sulfur dioxide fumigation. Ecotoxicol Environ Saf 178:9–16

Hasanuzzaman M, Hossain MA, da Silva JAT, Fujita M (2012) Plant response and tolerance to abiotic oxidative stress: antioxidant defense is a key factor. In: Tuteja N, Gill SS (eds) Crop stress and its management: perspectives and strategies. Springer, Dordrecht, pp 261–315

Hasegawa PM, Bressan RA, Zhu JK, Bohnert HJ (2000) Plant cellular and molecular responses to high salinity. Annu Rev Plant Biol 51:463–499

Hossain MA, Uddin SN (2011) Mechanisms of waterlogging tolerance in wheat: morphological and metabolic adaptations under hypoxia or anoxia. Aust J Crop Sci 5:1094–1101

Hu Y, Schmidhalter U (1997) Interactive effects of salinity and macronutrient level on wheat. II. Composition. J Plant Nutr 20:1169–1182

Hussain M, Malik MA, Farooq M, Ashraf MY, Cheema MA (2008) Improving drought tolerance by exogenous application of glycinebetaine and salicylic acid in sunflower. J Agron Crop Sci 194:193–199

Jackson MB (2006) Plant survival in wet environments: resilience and escape mediated by shoot systems. In: Bobbink R, Beltman B, Verhoeven JTA, Whigham DE (eds) Wetlands: functioning, biodiversity conservation, and restoration. Springer, Berlin, Heidelberg, pp 15–36

Jackson MB (2008) Ethylene-promoted elongation: an adaptation to submergence stress. Ann Bot 101:229–248

Jaleel CA, Manivannan P, Wahid A, Farooq M, Al-Juburi HJ, Somasundaram R, Panneerselvam R (2009) Drought stress in plants: a review on morphological characteristics and pigments composition. Int J Agric Biol 11:100–105

James RA, Davenport RJ, Munns R (2006) Physiological characterization of two genes for Na+ exclusion in durum wheat, Nax1 and Nax2. Plant Physiol 142:1537–1547

Jamil A, Riaz S, Ashraf M, Foolad MR (2011) Gene expression profiling of plants under salt stress. Crit Rev Plant Sci 30:435–458

Jeschke WD (1984) K+-Na+ exchange at cellular membranes, intracellular compartmentation of cations, and salt tolerance. In: Staples RC, Toenniessen GH (eds) Salinity tolerance in plants strategies for crop improvement. Wiley, Toronto, pp 37–66

Jiang W, Liu D (2010) Pb-induced cellular defense system in the root meristematic cells of *Allium sativum* L. BMC Plant Biol 10:40–48

Kalai T, Khamassi K, Teixeira da Silva JA, Gouia H, Bettaieb Ben-Kaab L (2014) Cadmium and copper stress affect seedling growth and enzymatic activities in germinating barley seeds. Arch Agron Soil Sci 60:765–783

Kalaji HM, Loboda T (2007) Photosystem II of barley seedlings under cadmium and lead stress. Plant Soil Environ 53:511–516

Kaloki P, Devasirvatham V, Tan DK (2019) Chickpea abiotic stresses: combating drought, heat and cold. In: Alexandre DO (ed) Abiotic and biotic stress in plants. IntechOpen, London, pp 725–729

Kaundal A, Sandhu D, Duenas M, Ferreira JF (2019) Expression of the high-affinity K+ transporter 1 (PpHKT1) gene from almond rootstock ‘Nemaguard’ improved salt tolerance of transgenic Arabidopsis. PLoS One 14:e0214473

Khan MA, Gul B (2006) Halophyte seed germination. In: Khan MA, Weber DJ (eds) Ecophysiology of high salinity tolerant plants. Springer, Dordrecht, pp 11–30

Khan MN, Zhan J, Luo T, Liu J, Ni F, Rizwan M, Fahad S, Hu L (2019) Morpho-physiological and biochemical responses of tolerant and sensitive rapeseed cultivars to drought stress during early seedling growth stage. Acta Physiol Plant 41:1–13

Khatun S, Rizzo CA, Flowers TJ (1995) Genotypic variation in the effect of salinity on fertility in rice. Plant Soil 173:239–250

Kim JY, Mahé A, Brangeon J, Prioul JL (2000) A maize vacuolar invertase, IVR2, is induced by water stress. Organ/tissue specificity and diurnal modulation of expression. Plant Physiol 124:71–84

Kirk GJD, Greenway H, Atwell BJ, Ismail AM, Colmer TD (2014) Adaptation of rice in flooded soil. In: Lüttge U, Beyschlag W, Cushman J (eds) Progress in botany. Springer, Berlin, pp 215–253

Klein M, Burla B, Martinoia E (2006) The multidrug resistance-associated protein (MRP/ABCC) subfamily of ATP-binding cassette transporters in plants. FEBS Lett 580:1112–1122

Kranner I, Colville L (2011) Metals and seeds: biochemical and molecular implications and their significance for seed germination. Environ Exp Bot 72:93–105

Krasensky J, Jonak C (2012) Drought, salt, and temperature stress-induced metabolic rearrangements and regulatory networks. J Exp Bot 63:1593–1608

Krishnan HB, Oehrle NW, Alaswad AA, Stevens WG, Maria John KM, Luthria DL, Natarajan SS (2019) Biochemical and anatomical investigation of *Sesbania herbacea* (Mill.) McVaugh nodules grown under flooded and non-flooded conditions. Int J Mol Sci 20:1–20

Kulichikhin K, Yamauchi T, Watanabe K, Nakazono M (2014) Biochemical and molecular characterization of rice (Oryza sativa L.) roots forming a barrier to radial oxygen loss. Plant Cell Environ 37:2406–2420

Kumar P, Pal M, Joshi R, Sairam RK (2013) Yield, growth and physiological responses of mung bean [*Vigna radiata* (L.) Wilczek] genotypes to waterlogging at vegetative stage. Physiol Mol Biol Plants 19:209–220

Kuzminov FI, Brown CM, Fadeev VV, Gorbunov MY (2013) Effects of metal toxicity on photosynthetic processes in coral symbionts, *Symbiodinium* spp. J Exp Mar Biol Ecol 446:216–227

Ladrera R, Marino D, Larrainzar E, González EM, Arrese-Igor C (2007) Reduced carbon availability to bacteroids and elevated ureides in nodules, but not in shoots, are involved in the nitrogen fixation response to early drought in soybean. Plant Physiol 145:539–546

Lahaye PA, Epstein E (1971) Calcium and salt toleration by bean plants. Physiol Plant 25:213–218

Lai JL, Luo XG (2019) High-efficiency antioxidant system, chelating system and stress-responsive genes enhance tolerance to cesium ionotoxicity in Indian mustard (*Brassica juncea* L.). Ecotoxicol Environ Saf 181:491–498

Landrigan PJ, Fuller R, Acosta NJ, Adeyi O, Arnold R, Baldé AB, Bertollini R, Bose-O'Reilly S, Boufford JI, Breysse PN, Chiles T (2018) The lancet commission on pollution and health. Lancet 391:462–512

Lawas LMF, Shi W, Yoshimoto M, Hasegawa T, Hincha DK, Zuther E, Jagadish SK (2018) Combined drought and heat stress impact during flowering and grain filling in contrasting rice cultivars grown under field conditions. Field Crops Res. 229:66–77

Lea-Cox JD, Syvertsen JP (1993) Salinity reduces water use and nitrate-N-use efficiency of citrus. Ann Bot 72:47–54

Lisar SY, Motafakkerazad R, Hossain MM, Rahman IM (2012) Water stress in plants: causes, effects and responses. In: Ismail MD, Mofizur R, Hiroshi H (eds) Water stress. IntechOpen, London, pp 1–15

Ma L, Coulter JA, Liu L, Zhao Y, Chang Y, Pu Y, Zeng X, Xu Y, Wu J, Fang Y, Bai J (2019) Transcriptome analysis reveals key cold-stress-responsive genes in winter rapeseed (*Brassica rapa* L.). Int J Mol Sci 20:1–19

Mahmood T, Mustafa HSB, Aftab M, Ali Q, Malik A (2019) Super canola: newly developed high yielding, lodging and drought tolerant double zero cultivar of rapeseed (*Brassica napus* L.). Genet Mol Res 18:gmr16039951

Makino T, Murakami M, Ishikawa S, Abe T (2019) Regulations for cadmium in Rice and soil in Japan and countermeasures to reduce the concentrations. In: Himeno S, Aoshima K (eds) Cadmium toxicity. Springer, Singapore, pp 103–114

Manickavelu A, Nadarajan N, Ganesh SK, Gnanamalar RP, Babu RC (2006) Drought tolerance in rice: morphological and molecular genetic consideration. Plant Growth Regul 50:121–138

Marchiol L, Assolari S, Sacco P, Zerbi G (2004) Phytoextraction of heavy metals by canola (*Brassica napus*) and radish (*Raphanus sativus*) grown on multicontaminated soil. Environ Pollut 132:21–27

Maryan KE, Lahiji HS, Farrokhi N, Komeleh HH (2019) Analysis of *Brassica napus* dehydrins and their co-expression regulatory networks in relation to cold stress. Gene Expr Patterns 31:7–17

Maxwell K, Johnson GN (2000) Chlorophyll fluorescence—a practical guide. J Exp Bot 51:659–668

Mensah JK, Obadoni BO, Eruotor PG, Onome-Irieguna F (2006) Simulated flooding and drought effects on germination, growth, and yield parameters of sesame (*Sesamum indicum* L.). Afr J Biotechnol 5:1249–1253

Mierek-Adamska A, Dąbrowska GB, Blindauer CA (2018) The type 4 metallothionein from *Brassica napus* seeds folds in a metal-dependent fashion and favours zinc over other metals. Metallomics 10:1430–1443

Munns R (2002a) Comparative physiology of salt and water stress. Plant Cell Environ 25:239–250

Munns R (2002b) Salinity, growth and phytohormones. In: Läuchli A, Lüttge U (eds) Salinity: environment-plants-molecules. Springer, Dordrecht, pp 271–290

Munns R (2005) Genes and salt tolerance: bringing them together. New Phytol 167:645–663

Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681

Ohnishi N, Wacera F, Sakamoto W (2019) Photosynthetic responses to high temperature and strong light suggest potential post-flowering drought tolerance of Sorghum Japanese landrace Takakibi. Plant Cell Physiol 60:2086–2099

Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK (2014) Climate change 2014: synthesis report. In: Pachauri R, Meyer L (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Ipcc, Geneva, p 151

Pan L, Yu X, Shao J, Liu Z, Gao T, Zheng Y, Chen C (2019) Transcriptomic profiling and analysis of differentially expressed genes in asparagus bean (*Vigna unguiculata* ssp. *sesquipedalis*) under salt stress. PLoS One 14:e0219799

Panozzo A, Dal Cortivo C, Ferrari M, Vicelli B, Varotto S, Vamerali T (2019) Morphological changes and expressions of AOX1A, CYP81D8 and putative PFP genes in a large set of commercial maize hybrids under extreme waterlogging. Front Plant Sci 10:1–14

Panuccio MR, Jacobsen SE, Akhtar SS, Muscolo A (2014) Effect of saline water on seed germination and early seedling growth of the halophyte quinoa. AoB Plants 6:plu047

Parelle J, Roudaut JP, Ducrey M (2006) Light acclimation and photosynthetic response of beech (*Fagus sylvatica* L.) saplings under artificial shading or natural Mediterranean conditions. Ann For Sci 63:257–266

Parent C, Capelli N, Berger A, Crèvecoeur M, Dat JF (2008) An overview of plant responses to soil waterlogging. Plant Stress 2:20–27

Park JH, Lamb D, Paneerselvam P, Choppala G, Bolan N, Chung JW (2011) Role of organic amendments on enhanced bioremediation of heavy metal (loid) contaminated soils. J Hazard Mater 185:549–574

Park HC, Hwang JE, Jiang Y, Kim YJ, Kim SH, Nguyen XC, Kim CY, Chung WS (2019) Functional characterisation of two phytochelatin synthases in rice (*Oryza sativa* cv. Milyang 117) that respond to cadmium stress. Plant Biol 21:854–861

Parra-Almuna L, Diaz-Cortez A, Ferrol N, de la Luz Mora M (2018) Aluminium toxicity and phosphate deficiency activates antioxidant systems and up-regulates expression of phosphate transporters gene in ryegrass (Lolium perenne L.) plants. Plant Physiol Biochem 130:445–454

Patel BB, Dave RS (2011) Studies on infiltration of saline-alkali soils of several parts of Mehsana and Patan districts of North Gujarat. J Appl Technol Environ Sanit 1:87–92

Paul K, Pauk J, Kondic-Spika A, Grausgruber H, Allahverdiyev T, Sass L, Vass I (2019) Co-occurrence of mild salinity and drought synergistically enhances biomass and grain retardation in wheat. Front Plant Sci 10:1–15

Pekcan V, Evci G, Yilmaz MI, Nalcaiyi ASB, Erdal SÇ, Cicek N, Ekmekci Y, Kaya Y (2015) Drought effects on yield traits of some sunflower inbred lines. Poljopr Sumar 61:101–107

Pierart A, Shahid M, Sejalon-Delmas N, Dumat C (2015) Antimony bioavailability: knowledge and research perspectives for sustainable agricultures. J Hazard Mater 289:219–234

Popović V, Miladinović J, Vidić M, Vučković S, Dolijanović Ž, Ikanović J, Zivanović LJ, Kolarić L (2015) Drought–limiting factors in soybean production. The effect of irrigation on yield of soybean [Glycine max (L.) Merr.]. Proceedings. Institute of PKB Agroekonomik, Belgrade, pp 11–21

Pourrut B, Shahid M, Douay F, Dumat C, Pinelli E (2013) Molecular mechanisms involved in lead uptake, toxicity and detoxification in higher plants. In: Gupta DK (ed) Heavy metal stress in plants. Springer, Berlin, Heidelberg, pp 121–147

Qadir M, Schubert S (2002) Degradation processes and nutrient constraints in sodic soils. Land Degrad Dev 13:275–294

Queiroz MS, Oliveira CE, Steiner F, Zuffo AM, Zoz T, Vendruscolo EP, Silva MV, Mello BFFR, Cabra RC, Menis FT (2019) Drought stresses on seed germination and early growth of maize and sorghum. J Agric Sci 11:310–318

Rajendran K, Tester M, Roy SJ (2009) Quantifying the three main components of salinity tolerance in cereals. Plant Cell Environ 32:237–249

Rathaur P, Ramteke PW, Raja W, John SA (2012) Isolation and characterization of nickel and cadmium tolerant plant growth promoting rhizobacteria from rhizosphere of *Withania somnifera*. J Environ Sci 6:253–261

Reddy MD, Mittra BN (1985) Effect of complete plant submergence at different growth stages on grain yield, yield components and nutrient content of rice. Plant Soil 86:379–386

Reddy KR, Krutz L, Gao W, Bellaloui N (2019) Poor seed quality, reduced germination, and decreased seedling vigor in soybean is linked to exposure of the maternal lines to drought stress. BioRxiv:590059 (in press)

Ren ZH, Gao JP, Li LG, Cai XL, Huang W, Chao DY, Zhu MZ, Wang ZY, Luan S, Lin HX (2005) A rice quantitative trait locus for salt tolerance encodes a sodium transporter. Nat Genet 37:1141–1146

Romero-Puertas MC, Rodríguez-Serrano M, Corpas FJ, Gomez MD, Del Rio LA, Sandalio LM (2004) Cadmium-induced subcellular accumulation of O2·− and H2O2 in pea leaves. Plant Cell Environ 27:1122–1134

Ronga D, Rizza F, Badeck FW, Milc J, Laviano L, Montevecchi G, Pecchioni N, Francia E (2018) Physiological responses to chilling in cultivars of processing tomato released and cultivated over the past decades in Southern Europe. Sci Hortic 231:118–125

Rozeff N (1995) Sugarcane and salinity—a review paper. Sugarcane 5:8–19

Sadak MS (2019) Physiological role of trehalose on enhancing salinity tolerance of wheat plant. Bull Natl Res Cent 43:1–10

Saha P, Chatterjee P, Biswas AK (2010) NaCl pretreatment alleviates salt stress by enhancement of antioxidant defense system and osmolyte accumulation in mungbean (Vigna radiata L. Wilczek). Indian J. Exp Biol 48:593–600

Sairam RK, Kumutha D, Ezhilmathi K, Deshmukh PS, Srivastava GC (2008) Physiology and biochemistry of waterlogging tolerance in plants. Biol Plant 52:401

Sakamoto A, Murata N (2002) The role of glycine betaine in the protection of plants from stress: clues from transgenic plants. Plant Cell Environ 25:163–171

Sánchez-Gómez D, Cervera MT, Escolano-Tercero MA, Vélez MD, de María N, Diaz L, Sánchez-Vioque R, Aranda I, Guevara MA (2019) Drought escape can provide high grain yields under early drought in lentils. Theor Exp Plant Physiol 31(2):273–286

Sapeta H, Costa JM, Lourenco T, Maroco J, Van der Linde P, Oliveira MM (2013) Drought stress response in *Jatropha curcas*: growth and physiology. Environ Exp Bot 85:76–84

Satir O, Berberoglu S (2016) Crop yield prediction under soil salinity using satellite derived vegetation indices. Field Crops Res 192:134–143

Sauter M (2013) Root responses to flooding. Curr Opin Plant Biol 16:282–286

Schulz E, Tohge T, Zuther E, Fernie AR, Hincha DK (2016) Flavonoids are determinants of freezing tolerance and cold acclimation in *Arabidopsis thaliana*. Sci Rep 6:1–14

Schulze ED, Beck E, Buchmann N, Clemens S, Müller-Hohenstein K, Scherer-Lorenzen M (2019) Water deficiency (Drought). In: Schulze ED, Beck E, Buchmann N (eds) Plant Ecology. Springer, Heidelberg, pp 162–202

Sculthorpe CD (1967) The biology of aquatic vascular plants. Edward Arnold Press, London, p 610

SEDAC (n.d.) Global flood hazard frequency and distribution, v1 (1985 – 2003). http://sedac.ciesin.columbia.edu/data/set/ndh-flood-hazard-frequency-distribution. Accessed 15 Oct 2019

Selpair S (2018) Analyzing reproductive capabilities of chickpea in cold environment. http://210.212.34.21/handle/32116/1952. Accessed 2 Mar 2018

Shahid M, Arshad M, Kaemmerer M, Pinelli E, Probst A, Baque D, Pradere P, Dumat C (2012) Long-term field metal extraction by Pelargonium: phytoextraction efficiency in relation to plant maturity. Int J Phytoremediation 14:493–505

Sharma N, Bisht SS, Gupta S, Panda AK, Rana M (2018) Analysis of proteomic diversity and calcium binding protein(s) in seeds of horse gram (*Macrotyloma uniflorum*) cultivars from Uttarakhand. Int J Pharm Sci Res 9:3274–3280

Shawon RA, Kang DH, Ryu CS, Kim DE, Lee SY, Bae JH, Kim YO, Ku YG (2017) Physiological responses and antioxidative enzyme activities in pepper (*Capsicum annuum*) seedlings under low temperature stress. J Agric Life Sci 51:67–77

Shiono K, Takahashi H, Colmer TD, Nakazono M (2008) Role of ethylene in acclimations to promote oxygen transport in roots of plants in waterlogged soils. Plant Sci 175:52–58

Shrivastava P, Kumar R (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J Biol Sci 22:123–131

Silva EN, Silveira JA, Aragão RM, Vieira CF, Carvalho FE (2019) Photosynthesis impairment and oxidative stress in *Jatropha curcas* exposed to drought are partially dependent on decreased catalase activity. Acta Physiol Plant 41:1–12

Singh S, Singh SP, Pathak AD, Pandey N (2019) Assessment of waterlogging induced physiobiochemical changes in sugarcane varieties and its association with waterlogging tolerance. J Environ Biol 40:384–392

Sinha S, Raxwal VK, Joshi B, Jagannath A, Katiyar-Agarwal S, Goel S, Kumar A, Agarwal M (2015) De novo transcriptome profiling of cold-stressed siliques during pod filling stages in Indian mustard (*Brassica juncea* L.). Front Plant Sci 6:1–17

Solaiman Z, Colmer TD, Loss SP, Thomson BD, Siddique KHM (2007) Growth responses of cool-season grain legumes to transient waterlogging. Aust J Agric Res 58:406–412

Souza SC, Mazzafera P, Sodek L (2016) Flooding of the root system in soybean: biochemical and molecular aspects of N metabolism in the nodule during stress and recovery. Amino Acids 48:1285–1295

Stvolinskaya NS (2000) Viability of *Taraxacum officinale* Wigg. in populations of the city of Moscow in relation to motor transport pollution. Russ J Ecol 31:129–131

Sudhir P, Murthy SDS (2004) Effects of salt stress on basic processes of photosynthesis. Photosynthetica 42:481–486

Suhayda CG, Giannini JL, Briskin DP, Shannon MC (1990) Electrostatic changes in *Lycopersicon esculentum* root plasma membrane resulting from salt stress. Plant Physiol 93:471–478

Taiz L, Zeiger E (2006) Plant physiology, 4th edn. Sinauer Associates, Sunderland, MA, pp 345–376

Tang H, Niu L, Wei J, Chen X, Chen Y (2019) Phosphorus limitation improved salt tolerance in maize through tissue mass density increase, osmolytes accumulation, and Na+ uptake inhibition. Front Plant Sci 10:1–10

Tarekegne A, Bennie ATP, Labuschagne MT (2000) Effects of soil waterlogging on the concentration and uptake of selected nutrients in wheat genotypes differing in tolerance. In: The eleventh regional wheat workshop for eastern, central and southern Africa, Addis Abeba, Ethiopia. CIMMYT, Addis Ababa, pp 253–263

Tewari S, Arora NK (2016) Soybean production under flooding stress and its mitigation using plant growth-promoting microbes. In: Mohammad M (ed) Environmental stresses in soybean production: soybean production, vol 2. Academic press, San Diego, pp 23–40

Turhan E, Ergin S (2012) Soluble sugars and sucrose-metabolizing enzymes related to cold acclimation of sweet cherry cultivars grafted on different rootstocks. Sci World J 2012:1–7

Turner NC, Wright GC, Siddique KHM (2001) Adaptation of grain legumes (pulses) to water-limited environments. Adv Agron 71:194–233

UNESCO (2018) Climate change and water security. https://en.unesco.org/themes/addressing-climate-change/climate-change-and-water-security. Accessed 12 Mar 2018

Vandoorne B, Descamps C, Mathieu AS, Van den Ende W, Vergauwen R, Javaux M, Lutts S (2014) Long term intermittent flooding stress affects plant growth and inulin synthesis of *Cichorium intybus* (var. sativum). Plant Soil 376:291–305

Wang Y, Zhang B, Jiang D, Chen G (2019) Silicon improves photosynthetic performance by optimizing thylakoid membrane protein components in rice under drought stress. Environ Exp Bot 158:117–124

Watts J (19 March 2018) Water shortages could affect 5bn people by 2050, UN report warns. The Guardian. https://www.theguardian.com/environment/2018/mar/19/water-shortages-could-affect-5bn-people-by-2050-un-report-warns. Accessed 31 Oct 2019

Wei H, Chen C, Ma X, Zhang Y, Han J, Mei H, Yu S (2017) Comparative analysis of expression profiles of panicle development among tolerant and sensitive rice in response to drought stress. Front Plant Sci 8:1–10

Williams G, Vanniarajan C, Vetriventhan M, Thiageshwari S, Anandhi K, Rajagopal B (2019) Genetic variability for seedling stage salinity tolerance in barnyard millet [*Echinochloa frumentacea* (Roxb.) Link]. Electron J Plant Breed 10:552–558

Wise RR, Naylor AW (1987) Chilling-enhanced photooxidation: the peroxidative destruction of lipids during chilling injury to photosynthesis and ultrastructure. Plant Physiol 83(2):272–277

Wise RR, Olson AJ, Schrader SM, Sharkey TD (2004) Electron transport is the functional limitation of photosynthesis in field-grown Pima cotton plants at high temperature. Plant Cell Environ 27:717–724

Wu G, Kang H, Zhang X, Shao H, Chu L, Ruan C (2010) A critical review on the bio-removal of hazardous heavy metals from contaminated soils: issues, progress, eco-environmental concerns and opportunities. J Hazard Mater 174:1–8

Wu GQ, Wang JL, Feng RJ, Li SJ, Wang CM (2018) iTRAQ-based comparative proteomic analysis provides insights into molecular mechanisms of salt tolerance in sugar beet (*Beta vulgaris* L.). Int J Mol Sci 19:1–20

Xiong ZT, Zhao F, Li MJ (2006) Lead toxicity in *Brassica pekinensis* Rupr.: effect on nitrate assimilation and growth. Environ Toxicol 21:147–153

Yadav P, Kaur R, Kanwar MK, Bhardwaj R, Sirhindi G, Wijaya L, Alyemeni MN, Ahmad P (2018) Ameliorative role of castasterone on copper metal toxicity by improving redox homeostasis in *Brassica juncea* L. J Plant Growth Regul 37:575–590

Yamauchi T, Colmer TD, Pedersen O, Nakazono M (2018) Regulation of root traits for internal aeration and tolerance to soil waterlogging-flooding stress. Plant Physiol 176:1118–1130

Yazaki K (2006) ABC transporters involved in the transport of plant secondary metabolites. FEBS Lett 580:1183–1191

Yin D, Chen S, Chen F, Guan Z, Fang W (2009) Morphological and physiological responses of two chrysanthemum cultivars differing in their tolerance to waterlogging. Environ Exp Bot 67:87–93

Yu B, Zhao CY, Li J, Li JY, Peng G (2015) Morphological, physiological, and biochemical responses of *Populus euphratica* to soil flooding. Photosynthetica 53:110–117

Zeng F, Ali S, Zhang H, Ouyang Y, Qiu B, Wu F, Zhang G (2011) The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. Environ Pollut 159:84–91

Zhang X, Wan S, Hao J, Hu J, Yang T, Zong X (2016) Large-scale evaluation of pea (*Pisum sativum* L.) germplasm for cold tolerance in the field during winter in Qingdao. Crop J 4:377–383

Zhang C, Bai T, Xie D, Wang Y, Zhang H, Chen Y, Ni Z (2019a) Effects of PEG-6000 simulation drought stress on seed germination of mango (*Mangiferca indica* L.). Nanfang Nongye Xuebao 50:600–606 (in Chinese)

Zhang W, Wang S, Yu F, Tang J, Shan X, Bao K, Yu L, Wang H, Fei Z, Li J (2019b) Genome-wide characterization and expression profiling of SWEET genes in cabbage (*Brassica oleracea* var. *capitata* L.) reveal their roles in chilling and clubroot disease responses. BMC Genomics 20:1–16

Zhao C, Yang R, Hong Y, Ren Z, Tang K, Zhang H, Zhu JK (2019) A role for PICKLE in the regulation of cold and salt stress tolerance in Arabidopsis. Front Plant Sci 10:1–11

Zheng C, Jiang D, Liu F, Dai T, Jing Q, Cao W (2009) Effects of salt and waterlogging stresses and their combination on leaf photosynthesis, chloroplast ATP synthesis, and antioxidant capacity in wheat. Plant Sci 176:575–582

Zhou M (2010) Improvement of plant waterlogging tolerance. In: Mancuso S, Shabala S (eds) Waterlogging signalling and tolerance in plants. Springer, Heidelberg, pp 267–285

Zhu JK (2001) Plant salt tolerance. Trends Plant Sci 6:66–71

Zinselmeier C, Jeong BR, Boyer JS (1999) Starch and the control of kernel number in maize at low water potentials. Plant Physiol 121:25–36

Zörb C, Geilfus CM, Dietz KJ (2019) Salinity and crop yield. Plant Biol 21:31–38