An Introduction to Abiotic Stress in Plants

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Chapter - 9

An Introduction to Abiotic Stress in Plants

Jagadish Jena, Soumya Kumar Sahoo and Goutam Kumar Dash

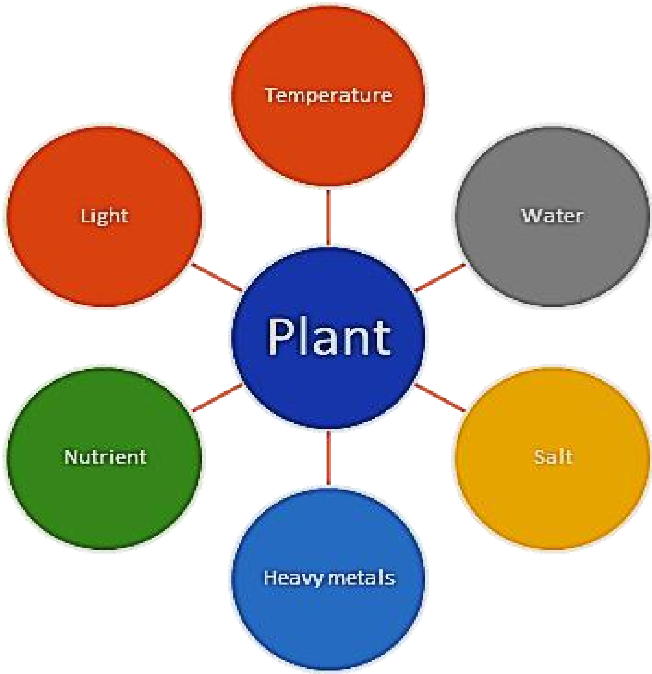
Abstract

Biological system is an endogenic and dynamic system which always seeks constant in-flow of energy to maintain its meta-stable condition called homeostasis. Any environmental disruption of this homeostasis may be explicated as biological stress. Biological stress limits the growth and yield potential of a crop and has been broadly grouped into biotic and abiotic stresses. Biotic stress conceives due to interactions between organisms starting from predation to allelopathy. Abiotic stress in the other hand appears due to the adverse effects of non-living environmental factors i.e. water, temperature, light, metal, mineral nutrients etc. on plants which are often sporadic and are highly localized. Both of these stresses are inevitable but can be minimized to some extent for increasing the productive potential of crops. Among the management practices for successful crop production in stress condition; breeding, biotechnology and agronomic approaches are widely used. In this chapter an attempt has been made to lucidly present the basic ideas about different types of stress and their impacts on crop production as well as some management approaches to minimize the effects of stress on crops.

Keywords: stress, abiotic stress, temperature stress, heavy metal stress, moisture stress, salinity stress, oxidative stress

Introduction

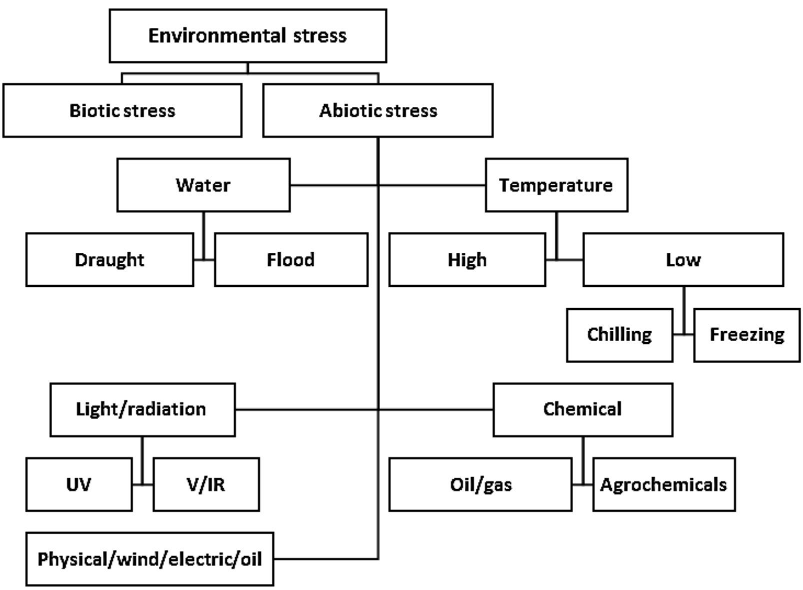
Climate change is a global issue pertaining abiotic and biotic stress on biosphere directly or indirectly reducing their production and productivity. The concept of stress first developed by Hans Selye in 1936 as unfavorable environmental limitations for plants (Selye H., 1936). Physically, stress is the force per unit area which causes dimensional change on which the stress applied. Biologically, stress is the factors that reduces normal function of individual which limits their genetic potential for growth, development and reproduction (Levitt, 1980). In agricultural context, stress is the factor that reduces crop productivity and destroys biomass (Grime, 1979). According to Levitt, stress is any environmental factor potentially unfavorable to living organisms (Levitt, 1980). Lichtenthaler extended the concept of plant stress including regeneration phase of plant, differentiating eustress and di-stress (Lichtenthaller, 1988 & 1996). Based on involvement of factors that causes stress, stress can be broadly divided into biotic stress which is the function of interaction between organisms for resources, predation and allelopathic effects and abiotic stress which is the interaction between organism and physical environment. Abiotic factors limit choice of crops, production in large areas and extreme events lead to total crop failure.



Global climate abnormalities due to different anthropogenic and natural activities typically increased different biotic and abiotic stress on crop plants which affect plants genetic potential of growth and economic production adversely (Prasad *et al*., 2011; Mahalingam, 2015; Ramegowda and Senthil-Kumar, 2015). Abiotic stress i.e. moisture stress, temperature stress, salinity stress etc. influence occurrence of different biotic stress i.e. pathogens, insects and weeds (Ziska *et al*., 2010; Peters *et al*., 2014) at different crop growth stages (Mittler, 2006; Prasad *et al*., 2011). Abiotic stress may result minor pest to become a potential threat (Duveiller *et al*., 2007) and may alter plant physiology and defense responses (Scherm and Coakley, 2003). There are different types of interactions exist between different stress mechanisms and the effect of these interactions on plant growth and productivity may be better understood from "stress matrix" developed by Mittler and colleagues (Mittler, 2006; Suzuki *et al*., 2014).

Concepts and types of stress

Stress is the factor that exert disadvantageous impacts on plant resulting in unfavorable consequences. This factor may by abiotic i.e. climate and soil or biotic i.e. weeds, pathogens, insects etc. Different types of stress may have different duration for its impact i.e. air temperature can become stressful in few minutes but soil mineral deficiency can take months to become stressful. Stress is measured in terms of plants survival, growth and yield or primary assimilation process i.e. photosynthetic rate, nutrient accumulation, growth rate etc. Stress may be *elastic* when plant recovers with the withdrawal of the stress factor or *plastic* when plants deformed and the change is irreversible after implication of the stress factor.



- **Draught:** It is the stress caused by combination of physical factors reducing water (low moisture stress) availability to the plant sufficient enough to retard the growth and development
- **Flood:** It is the stress caused by excess moisture in the root zone that retard gas exchange (mainly O_2) between soil environment and plant root causing hypoxic condition

- **Heat injury:** Stress caused by temperature more than threshold that can be tolerated by plant i.e. mostly more than 40 °C. When high temperature crosses thermal death point, it leads to death of the plant
- **Freezing/frost injury:** Stress caused by sub-zero temperature i.e. 0 °C or 0 to-10 °C when most of the actively grown plants get killed or injured
- **Chilling injury:** Stress caused by low temperature i.e. 10 to 15 °C or less but more than 0 °C that cause injury mostly in warm season crops i.e. rice, maize, sorghum etc.
- **Radiation injury:** Stress caused by electro-magnetic radiations i.e. UV radiation causing mutation or degradation of biomolecules or IR radiation causing heat injury in plants
- **Salt stress:** Stress caused due to excess soluble salt accumulation in root zone causing specific ion effect or disturbance in mineral nutrient uptake or increasing osmotic potential

Temperature stress

Tropical climate is cursed with higher temperature and radiation which limits the plant growth and development. High temperature causes scorching, sunburn and discolouration of leaves which reduces growth of plants (Vollenweider and Gunthardt-Goerge, 2005). Stress that limits growth, metabolism, and yield potential due to exposure of temperature below or above the thermal threshold for optimal biochemical, physiological and morphological development is called temperature stress (Greaves, 1996). Plants are classified as psychrophiles, mesophiles and thermophiles according to their tolerance to low, medium and high temperature (Levitt, 1980). Adversity of heat stress varies with duration, stage and intensity of the stress (Fahad *et al*., 2016b). Increase in heat stress reduces numbers of spikelets, numbers of florets per plant in rice, seed set in sorghum (Prasad et. 2006; Fahad *et al*., 2016b). It has also adverse effects on net assimilation rate and growth in maize and sugarcane and it also reduces nodal length, biomass accumulation, early leaf senescence in sugarcane (Ashraf & Hafeez, 2004; Wahid *et al*., 2007). Heat stress reduces yield about 50%, 31% and 42% in rice, wheat and maize respectively (Li *et al*., 2010; Balla *et al*., 2011; Badu-Apaku *et al*., 1983). It also reduces the quality due to reduced production of oil, starch and protein (Wilhelm *et al*., 1999; Maestri *et al*., 2002).

With the severity of heat stress growth, mass and number of roots reduces significantly due to reduction of water and nutrient supply (Wahid *et* *al*., 2007; Hall *et al*., 2012). Heat stress under limited water supply is proved to be fatal (Machado and Paulsen, 2001). It deactivates enzyme used in chlorophyll biosynthesis (Dutta *et al*., 2009) which increases the degradation of chlorophyll a & b in developed leaves (Karim *et al*., 1999). This degradation also associated with oxidative damage. Despite all the physiological biochemical impacts of increased heat stress, the optimum temperature for photosynthetic activity expected to increase with elevated concentration of CO_2 in atmosphere. The injury process in high temperature stress progresses from direct reversible strain i.e. respiration more than photosynthesis to indirect strain i.e. draught or direct strain i.e. starvation (Levitt, 1980). Heat stress tolerant plants show minimal damage to photosynthetic organs, process and increase in biosynthesis of protective compounds (Bita and Gerats, 2013) and the ideal plant types for better tolerance to heat stress should have better photosynthetic rate, membrane thermo-stability and fruit setting and fruit setting under high temperature (Nagarajan *et al*., 2010).

Heat stress can be managed by developing heat tolerant cultivars through conventional breeding (Ehlers and Hall, 1998), QTLs for grain filling and leaf senescence, heat tolerance during reproductive stage and stay green properties Farooq *et al*., 2011; Kumar *et al*., 2010) and their application in transgenic development (Bohnert *et al*., 2006). Some other heat stress management approaches include pre-conditioning of plants (Morales *et al*., 2003), pre-sowing or early sowing (Tikhomirova, 1985), application of Ca (Jiang and Huang, 2001), application of Glycine and Betain (Wahid and Shabir, 2005) and application of spermidine (Murkowski, 2001).

Low temperature stress cause wilting, bleaching, browning, necrosis and plant death (Levitt, 1980; Witt and Barfield, 1982). About 15% arable land estimated to be affected by freezing stress (Dudal, 1976).

Moisture stress

Around 28% of world's land are too dry for agricultural support (Kramer and Bouyer, 1995). Estimated annual yield loss due to draught in tropics is nearly 17% (Edmeades *et al*., 1992). Increased draught with the changing climate scenario results in decrease in physiology, plant growth and reproduction (Barnabas *et al*., 2008). Daryanto *et al* (2016) reported 21% and 40% yield reduction in wheat and maize respectively due to draught. Draught causes increase in transpiration and reduce water availability to plants roots (Anjum *et al*., 2011) which tends water balance in negative side affecting growth, nutrient and water relation, photosynthesis and assimilate partitioning and ultimately the yield (Farooq *et al*., 2009). Draught stress response in plants varies among species depending on their stages and other growth factors (Demirevska *et al*., 2010). High temperature stress affect enzyme activity, cell division in plants (Smertenko, 1997) and also changes growing period and distribution of agricultural crops (Porter, 2005).

Draught reduces germination and seedling growth (Kaya *et al*., 2006; Farooq *et al*., 2009), reduction in early seedling growth, length of hypocotyl, root and shoot dry weight, vegetative growth in field crops like pea, alfalfa, rice (Manikavelu *et al*., 2006; Zeid and Shedeed, 2006). Poor crop growth during draught stress mainly due to reduction in cell turgidity (Taiz and Zeiger, 2006) and reduction in mitosis and cell elongation (Hussain *et al*., 2008). Decreased turgidity reduce leaf expansion causing reduction in photosynthesis and plant growth (Rucker *et al*., 1995). Pre-anthesis occurrence of draught stress causes early anthesis, while post-anthesis stress causes early grain filling in cereals (Estrada-Campuzano *et al*., 2008). The decrease in activity of enzymes i.e. sucrose synthase, starch synthase, starch branching enzyme and adenosine di-phosphate glucose pyrophosphorylase which controls grain filling in cereals (Taiz and Zeiger, 2006) is the main cause of yield reduction in cereals (Ahmadi and Baker, 2001). Reduction in rate of photosynthesis (Bota *et al*., 2004), change in assimilate partitioning (Farooq *et al*., 2009b) and reduction in flag leaf development (Rucker *et al*., 1995) are the main causes of yield reduction due to draught stress. Yield loss of 53-92%, 57%, 63-87 reported in rice, wheat and maize respectively due to draught stress (Lafitte *et al*., 2007; Balla *et al*., 2011).

Drought stress management can be done by conventional breeding of stress tolerant plant with cultivar having good agronomic performance (Ashraf, 2010), QTL mapping followed by MAS approach (Ashraf *et al*., 2008), transgenic approach (Ashraf, 2010) and induced stress tolerance i.e. priming (Farooq *et al*., 2008; Bajwa and Farooq, 2016).

Heavy metal stress

Heavy metals (53 nos.) are those having specific gravity more than 5 g cm^{-3} or atomic mass over 20 and are generally toxic at even low concentration (Sharma and Dietz, 2006; Rascio and Navari-Izzo, 2011) i.e. Cadmium (Cd), Lead (Pb), Arsenic (As), Silver (Ag) etc. Heavy metal contamination in soil are mainly due to human activities i.e. mining, smelting, intensive agricultural practices, fuel production, electroplating etc. (Dembitsky, 2003; Igwe and Abia, 2006; Ali *et al*., 2013) and may also be due to natural processes i.e. soil erosion, excessive weathering of rocks and minerals and volcanic eruption. Among heavy metals, some have known physiological functions in plant system called nonessential heavy metals i.e. Arsenic (As), Lead (Pb), Cadmium (Cd), Mercury (Hg) and Selenium (Se) and some are involved in different plant physiological functions like co-factor for enzymatic reactions (Mildvan, 1970) or role in redox reactions (Yruela, 2009) called essential heavy metals i.e. Cobalt (Co), Copper (Cu), Manganese (Mn), Zinc (Zn), Iron (Fe), Molybdenum (Mo) and Nickel (Ni).

Zn accumulation become phytotoxic and inhibits growth by root thickening, reducing cell division and elongation, inhibiting radicle emergence when accumulated at an early stage (Rout and Das, 2009). Increased Zn concentration resulted in disintegration of cell organelles and disruption of membrane in Pigeon pea (Sresty and Rao, 1999), distorted growth in root and leaf of wheat (Pearson and Rengel, 1995) and Mediterranean seagrass (Malea *et al*., 1995). Ni accumulation above optimal concentration have lethal effect on crop lifecycle, disturbs ionic balance in plant organs (Seregin *et al*., 2006), show Mg and Fe chlorosis (Piccini and Malavolta, 1992), induce moisture content followed by disturbing stomatal conductance and photosynthetic activity in cabbage (Molas, 1997) and disturb plant nutrient homeostasis and equilibrium (Rubio *et al*., 1994). Cd is a nonessential heavy metal and its hyper accumulation causes stunted growth and chlorosis in plants because of reduced Fe uptake (Haghiri, 1974), interfere transport and uptake essential nutrients i.e. P, K, Ca, Mg, Mn etc. and plant water uptake (Godbold and Hutterrmann, 1985).

The removal of these heavy metals from root zone of soil may done economically and efficiently using phytoremediation techniques (Salt *et al*., 1995) that includes phytoextraction, phytosequestration, phytodegradation, phytovolatilization, phytohydraulics and rhizodegradation (Tsao, 2003). Phytoextraction one of the attractive tools among these phytoremediation techniques which uses hyperaccumulators i.e. species from Arabidopsis, Thalaspi and Pteris genus (Hanikenne *et al*., 2008 and Blande *et al*., 2017) which can accumulate extremely high levels of heavy metals in their aerial parts without any toxic sign (Rascio and Navari-Izzo, 2011). Generally, plants containing higher than 0.1 mg g^{-1} of Cd, 1 mg g^{-1} of As, Cu, Cr, Co, Pb, Ni or 10 mg g^{-1} of Mg or Zn in their dry matter are considered to be as metal hyperaccumulators (Salt *et al*., 1998). There are certain mechanisms for heavy metal tolerance in hyperaccumulators i.e. enhanced uptake in root symplasm, efficient xylem loading for root to shoot transport, complex formation with nicotinamine for transport, accumulation mainly in aerial organs, complex formation with weak ligands such as malate or citrate for storage, sequester generally in vacuole of epidermal cells and strongly enhanced anti-oxidants whereas, heavy metal tolerance mechanism in non-hyperaccumulators are i.e. metals mostly accumulated in roots, small amount translocated into shoots, small portion accumulated in epidermal and mesophyll cells of shoots, form complexes with strong ligands such as PCs, glutathione for storage and enhanced anti-oxidants. There are also certain gene families or biosynthesis pathways with respect to adaptation mechanisms in plants under heavy metal stress conditions during phytoremediation which can be used for transgenic plant development which may capable of remediating heavy metals in soil.

Salt/salinity stress

Crop said to be in salt stress when it is unable to express its full genetic potential in terms of growth, development and reproduction as the salinity in the soil exceeds the critical level (Grieve *et al*., 2012). The composition and concentration of dissolved salts in soil and irrigation water varies from one place to another (Tanji and Wallender, 2012). The adverse effect of salt affected soils may be due to high salt concentration in the soil solution i.e. osmotic effects or by high concentration of specific ions such as sodium or chloride that can cause injury to sensitive crops i.e. specific ion effect. Adverse effect of saline soil is due to soluble salt concentration whereas, adverse effects of sodic soil is due to deterioration of soil physical condition (Shainberg and Singer, 2012).

The adverse effect of salt stress may be due to specific ion effect i.e. Na^+ and Cl-(Kingsbury and Epstein, 1986; Munns and Termaat, 1986) or interacting with other mineral nutrient dynamics (Shabala and Munns, 2012).

Most of the plants are non-halophytes or glycophytes which hardly tolerate high salt concentration i.e. rice, wheat, peas etc. and some plants are halophytes in nature which can tolerate high salt concentration and are from native flora of extremely saline soils i.e. mangroves, *Atriplex* spp., *Salicornia* spp. etc. Most of the osmotic adjustments can be achieved due to either the absorption or accumulation of ions from the medium or by synthesis and accumulating organic solutes and their dominance dependent on the type of plants and the level of salinity. Halophytes are generally adapted to high saline environment by accumulating excess absorbing salts in osmoticum in vacuole (Flowers and Colmer, 2008) or osmotic adjustment by different organic solutes in the cytoplasm (Wyn Jones and Gorham, 2002), sequestering excess salt from metabolically active tissues in salt glands and salt bladders (Flowers and Colmer, 2008; Shabala and Munns, 2012), secretion of compatible solutes or osmolytes i.e. proline, glycine betain and sucrose (Munns and Tester, 2008), osmoprotectant nature of these organic solutes (McNeil *et al.*, 1999), ion selective absorption and compartmentalization (Flowers, 2008), scavenging of reactive oxygen species (Viswanathan *et al.*, 2001) and salt tolerant gene expression (Byrt *et al.*, 2014).

Nutrient stress

There are several mineral elements contributing to the growth and development of a plant, among which 17 are called essential nutrients according to the essentiality criteria defined by Arnon and Stout. Mineral nutrition being an independent discipline of plant physiology (Grossman and Takahashi, 2001), essential minerals are further divided into four groups by Mengel and Kirkby (1978) according to their biological structures and metabolic functions. There is certain nutrient stress (deficiency or excess) reported by several scientists in different plants. Nitrate may be involved in biosynthesis and transport of cytokinin (Liu *et al.*, 2000) and higher level of nitrate (NO_3^-) inhibits root growth and root: shoot ratio (Zhang *et al.*, 1999). Phosphorous deficiency limited primary root elongation and enhance lateral root formation (Hodge, 2004), decrease shoot-root dry weight ratio (Fredeen *et al.*, 1989), reduce leaf number (Lynch *et al.*, 1991), affect formation of reproductive organs (Barry and Miller, 1989), decreased photosynthetic rate in soybean (Lauer *et al.*, 1989) and induced the expression of phosphoenolpyruvate carboxylase (PEPCO) in tobacco (Toyota *et al.*, 2003). Potassium (K^+) deficient plants are susceptible to lodging and draught (Lindhauer, 1985). Sulfur deficiency decreased net photosynthesis and root hydraulic conductivity (Karmoker *et al.*, 1991), decrease in shoot-root dry weight ratio (Edelbauer, 1980), impaired carbohydrate metabolism followed by induced starch accumulation (Willenbrink, 1967). Calcium deficiency cause premature fruit and bud shedding and excess calcium interferes magnesium absorption. Magnesium deficiency cause superoxide free radical accumulation (Cakmak and Marschner, 1992). Iron deficient plants are low in chlorophyll content, inhibit photosynthetic electron transport with reduced RUBP regeneration, responsible for low starch and sugar content and low CO_2 fixation (Sharma and Sanwal, 1992). Iron toxicity in water logged soil may cause bronzing, stunted top and root growth. Siderophores are the organic molecules which combine with iron and make it available to plants and microbes (Brown *et al.*, 1991). Manganese deficiency caused reduced root growth (Marcar and Graham, 1987) and some other typical deficiency symptoms of manganese deficiency in plants are *grey speck* of oats, *marsh* *spot* of pea and *Pahala blight* of sugarcane. Zinc deficiency causes decrease in protein content may be attributed due to unstable ribosomes (Obata and Umbebayashi, 1988) and low level of RNA (Cakmak *et al*., 1989) in low zinc availability. Copper deficiency in the leaves of subterranean clover reduced activity of polyphenol oxidase (Delhaize *et al*., 1985). Copper deficiency also decreased activity of IAA oxidase and peroxidase (Davies *et al*., 1978). It also causes die back in citrus, interveinal chlorosis and distorted lamina in legumes and tomato. Molybdenum deficiency in mustard leaves showed reduced level of DNA and RNA (Chatterjee *et al*., 1985). Molybdenum deficient plants are less resistant to low temperature and water logging stress (Vunkova-Radeva *et al*., 1988). The common boron deficiency symptoms are tobacco "top sickness", sugar beet "heart rot", celery "stem crack" and cauliflower "hollow heart". Boron deficiency inhibit DNA synthesis (Krueger *et al*., 1987), depressed cytokinin synthesis in sunflower (Wagner and Michael, 1971) and decrease RNA content due to enhanced RNase activity (Dave and Kannan, 1980).

Oxidative stress

Molecular oxygen (O_2) in atmosphere are results of photosynthesis and are required for basic aerobic life. O_2 fixed in various biomolecules by different non-enzymatic and enzymatic processes (Gilbert, 1981; Elstner, 1982, 1987). Ground state dioxygen (O_2) is unreactive for biomolecules but its physical activation i.e. singlet oxygen or chemical activation i.e. superoxide (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH) are biologically toxic (McKersie and Leshem, 1994). Superoxide and hydrogen peroxide both can be act as oxidant and reductant but hydroxyl radicals are the most powerful oxidizing agent that don't have any specific scavenger to neutralize it. Different reactive oxygen species (ROS) i.e. O_2^-, H_2O_2 and OH causes bleaching by chlorophyll degradation, lipid peroxidation, inhibition of sensitive enzymes, base alteration of DNA (Kasai *et al*., 1986), proteolysis (Wolff *et al*., 1986) etc. Reactive oxygen species are produced in chloroplast (Asada, 2006), mitochondria, endoplasmic reticulum, peroxisomes and glyoxysomes, plasma membrane and the apoplast compartment (McKersie and Leshem, 1994).

ROS in plants generally formed whenever they are subjected to different stress i.e. photoinhibition (Sonoike, 1996), herbicide, toxins and triazole compounds (Kauss and Jeblick, 1995), heavy metal toxicity (Foyer *et al*., 1994), UV radiation (Hideg and Vass, 1996), salt stress (Miszalski *et al*., 1998), draught and heat stress (Filek *et al*., 1997; Biemelt *et al*., 1998), chilling and freezing (Tao *et al*., 1998).

There are several defense systems in plants to protect plants from these ROS i.e. superoxide dismutase (SOD), ascorbate peroxidase, glutathione reductase (GR), mono-dehydroxy ascorbate reductase, catalase (CATs). Except these enzymatic antioxidants, there are some non-enzymatic antioxidants which play important role to protect biomolecules from ROS i.e. ascorbate, tocopherol, carotenoids, glutathione etc. Among all these antioxidants, SOD gives primary defense against oxygen free radicals (Bannister *et al.*, 1987) converting O_2^- to H_2O_2 and protects plants from different stress (Mittler and Zilinskas, 1994; Allen *et al.*, 1997).

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