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Biochemical Effects of Air Pollutants on Plants

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Abstract

Urbanization and industrialization processes contribute significant amount of various air pollutants such as SO_2, NO_2, CO, particulate matter, etc. These pollutants affect plant health and emit various forms of SO_2, NOx, and O_3 which may act in combination of a variety of ways: additive, synergistic, and antagonistic. These pollutants can have a deleterious effect on a variety of biochemical and physiological processes and on the structural organization within the cells. Certain plant species are very sensitive to these pollutants resulting in well visible and measurable symptoms. Morphological damage is generally visible through lesions on the leaves, flowers, and fruits while biochemical and physiological changes which are invisible can be measured and quantified. In this chapter, biochemical effects on plants have been described. These symptoms can be used as indicators of air pollution stress for its early diagnosis and can be used as markers for a particular physiological disorder.

Keywords

Urbanization • Industrialization • Biochemical • Physiological • Morphological • Air pollution stress

6.1 Introduction

Increasing air pollution has been a matter of concern for plant health due to its adverse effects on plant physiology, biochemistry, and morphology. Some of the atmospheric gases at their supra optimum level become pollutants and evoke various types of visible and hidden plant responses which ultimately lead to reduced plant growth and productivity (Krupa et al. 1982; Srivastava 1999; Poschl 2005). The impact of such anthropogenic emission into the atmosphere and its movement into the biosphere by transformation, reaction, and modification is responsible for a variety of chronic and acute diseases at local,

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regional, and global scales (Rawat and Banerjee 1996). Impact on the plant community has also been studied worldwide in terms of plant–environment interactions, since the plants are much more sensitive in comparison to other organisms (Abbasi et al. 2004). The symptoms or effects in plant anatomy, physiology, or biochemistry indicate the state of the environment. Since the major system and organs of plants are exposed to the atmosphere and the leaves continuously exchange gases in and out of the systems, any change in the atmosphere is reflected in the plants' physiology.

On the other hand, plants play an important role in monitoring and maintaining the ecological balance by actively participating in the cycling of nutrients and gases like carbon dioxide and oxygen and also provide enormous leaf area for impingement, absorption, and accumulation of air pollutants to reduce the pollution level in the air environment (Escobedo et al. 2008). Biomonitoring of air pollution using plants is possible by using both native and cultivated plant species present in the studied area (Shannigrahi et al. 2004). Plants take these air pollutants from the surrounding air. Once taken, the selected pollutant may be adsorbed, absorbed, accumulated, or integrated into the plant body. If the nature of a particular air pollutant is toxic, it may injure the plant exhibiting specific symptoms. Generally, sensitive species show quicker injury symptoms than that of tolerant ones. Hence, sensitive species act as early warning indicators of pollution. On the other hand, the tolerant species help in the scavenging of air pollutants, reducing the overall pollution load (Rao 1983). Among various air pollutants, gases such as SO_2, NO_2, HF, PAN, and O_3 are highly phytotoxic. These may harm higher plants very rapidly in a drastic manner (Figs. 6.1 and 6.2). For example, the phytotoxic effect of hydrogen fluoride (HF) is well known for several plant species such as monocotyledonous ornamental plants (as tulips, gladioli), stone fruit species (as plums, peaches, and apricots), crops (like maize), and natural plants (like *Hypericum perforatum* L. and *Picea abies* L.) (Flowers et al. 2007). When plants are exposed to HF air pollution, the F^- ion accumulates in the rims and tips of the leaves and causes necrosis of leaf tissue, clearly separated from the living, green tissue by a red-brown boundary zone (Fig. 6.3) (Hogue et al. 2007).

Air pollutants cause damage to leaf cuticles and affect stomatal conductance. They can also have direct effects on photosynthetic systems, leaf longevity, and patterns of carbon allocation within plants. Pollutants interact with other environmental factors and may alter plant–environment relationships on a regional scale (Winner 1981). Air pollutants' impact on plant life are mainly of two types – directly through clear visible leaf injury (e.g., interveinal or needle chlorosis and necrosis) or indirectly on growth and reproduction. Some air pollutants cause only visible effects on plants at a much higher concentration than indirect ones. For example, chlorine (Cl_2), nitrogen dioxide (NO_2), hydrochloric acid (HCI), and ammonia (NH_3) are components that do not produce specific symptoms, but all give rise to leaf chlorosis and necrosis and growth reduction (Weinstein 1977). Thus higher plants may be used as indicators and

Fig. 6.1 Effect of PAN on milkweed leaves (Source: https://extension.umd.edu/learn/air-pollution-effects-vegetables)

Fig. 6.2 Effect of ozone on potato (Source: https://extension.umd.edu/learn/air-pollution-effects-vegetables)

Fig. 6.3 Effect of hydrogen fluoride on *Dracaena deremensis* (Source: http://mysticablog.wordpress.com)

accumulators of air pollutants for detection, recognition, and monitoring purposes. Some of the important physiological processes such as photosynthesis, respiration, carbon allocation, and stomatal functioning are known to be effected by air pollution (Darrall 1988). Certain plant species may accumulate a particular component from the air without changing it in such a way that the component can be analyzed physiochemically (qualitatively and quantitatively) after accumulation in the plants (Hung and Mackay 1997). The level of biochemical parameters such as chlorophyll, protein, soluble sugar, ascorbic acid, superoxide dismutase, and peroxidase in leaves have been found to be pollution load dependent. The effect of pollution on each of these biochemical constituents has been described below.

6.2 Effect on Pigment Content

Chlorophyll is one of the main essential parts of energy production in green plants and its amounts are significantly affected by environmental condition. Depletion in chlorophyll causes a decrease in the productivity of plants and subsequently causes plants to exhibit poor vigor. The total chlorophyll level in plants decreases under stress condition (Speeding and Thomas 1973). Bell and Mudd (1976) opined that tolerance of plants to SO_2 might be linked with the synthesis of degradation of chlorophyll. However plants maintaining their chlorophyll under polluted conditions are said to be tolerant (Singh and Verma 2007). Chlorophyll measurement is an important tool to evaluate the effects of air pollutants on the plants as it plays an important role in plant metabolism. Any reduction in chlorophyll content directly affects plant growth (Agbaire and Esiefarienhre 2009). The net photosynthetic rate is a commonly used indicator of impact of increased air pollutants on plant growth (Woo et al. 2007). Air pollution stress leads to stomatal closure, which reduces CO_2 availability in leaves and inhibits carbon fixation. Sulfur dioxides, nitrogen dioxides, and CO_2, as well as suspended particulate matter, are some of the air pollutants which are absorbed by plant leaves causing reduction in the levels of photosynthetic pigments, viz., chlorophyll and carotenoids, affecting the plant productivity directly (Joshi and Swami 2009; Honour et al. 2009). Rao and LeBlanc (1965) found that destruction of chlorophyll occurred in lichens following exposure to large doses (5 ppm for 24 h) of gaseous SOx. At this high concentration, chlorophyll molecules were degraded to pheophytin and Mg^{2+}. A similar conversion of chlorophyll to pheophytin can occur with acids or acidic substances. In this process Mg^{2+} in the chlorophyll molecule is replaced by two atoms of hydrogen, thereby changing the light-spectrum characteristic of the chlorophyll molecules. Rapid in vitro chlorophyll destruction can also be caused by free radicals produced during the oxidation of HSO_3^--catalyzed decomposition of the linoleic acid hydrogen peroxide (Peiser and Yang 1977, 1979). Shimazaki et al. (1980) presented evidence that SO_2 fumigation of leaves increases the formation of O_2^- in chloroplasts that in turn destroys chlorophylls. A superoxide radical has been shown to influence chlorophyll at very low concentrations (10–8 to 10–7 M) (Asada et al. 1977). In *Spinacia oleracea* leaves, gaseous SO_2 destroyed chlorophyll a more rapidly than chlorophyll b, but the loss of chlorophyll a was not accompanied by a corresponding increase in pheophytin a (Shimazaki et al. 1980). As scavengers of free radicals inhibited chlorophyll breakdown in *Spinacia oleracea* leaves, it was suggested that SO_2 destroys chlorophyll mainly by a free-radical oxidation. This was further supported by the observation that chlorophyll a breakdown was inhibited by superoxide dismutase. Sulfur dioxide inhibits the superoxide dismutase activity in the fumigated tissues (Shimazaki et al. 1980). Furthermore, accumulation of malondialdehyde, a lipid peroxidation product, and a decrease in chlorophyll a in SO_2-fumigated *Spinacia oleracea* leaves were related to the free-radical oxidation of chlorophyll.

Gradual disappearance of chlorophyll and concomitant yellowing of leaves is one of the most common effects on plants which may be associated with the continuously decreasing photosynthetic capacity of the plant (Joshi et al. 2009). Carotenoids which help in capturing light in the chloroplast are also affected by air pollution. Carotenoids also play a more important role in protecting the cells and live organisms as they encounter damage from free-radical oxidative cells (Fleschin et al. 2003). These pigments are more stronger than chlorophyll but much less efficient in light gathering, help the valuable but much fragile chlorophyll, and protect chlorophyll from photoxidative destruction (Joshi et al. 2009). Similar to chlorophyll, the level of carotenoids decreases with the increase in air pollution load (Joshi et al. 2009; Tripathi and Gautam 2007; Tiwari et al. 2006; Gupta et al. 2015).

6.3 Effect on Sugar Content

Soluble sugars have osmoprotectant and cryoprotectant roles and their presence is important for the plasma membrane. These are important parts in the plant structure and source of energy in all organisms. The concentration of soluble sugars is indicative of the physiological activity of a plant and it determines the sensitivity of plants to air pollution (Tripathi and Gautam 2007). Accumulation of sugars in different parts of plants is enhanced in response to the variety of environmental stresses (Prado et al. 2000). Soluble sugars have been also reported to play a protective role against stresses (Finkelstein and Gibson 2001). In this study, there was an increase in soluble sugar in polluted sites indicative of stress. Soluble sugar is an important constituent of plants which acts as a source of energy. Plants manufacture sugars during photosynthesis and breakdown during respiration (Bennett et al. 1984). The concentration of soluble sugars is indicative of the physiological activity of a plant which determines the sensitivity of plants toward air pollution. Reduction in soluble sugar content at polluted sites can be attributed to the increased rate of respiration and decreased CO_2 fixation because of chlorophyll deterioration (Wilkinson and Barnes 1973). In a polluted environment, gases such as SO_2, NO_2, and H_2S can cause more depletion of soluble sugars in the leaves under hardening conditions. In an SO_2-exposed plant, the carbohydrate content is reduced due to sulfite reaction with aldehydes and ketones of carbohydrates (Dugger and Ting 1970). Plants exposed to SO_2 exhibit increasing amounts of soluble sugars (Khan and Malhotra 1977; Koziol and Jordan 1978; Malhotra and Sarkar 1979). In *Pinus banksiana*, SO_2 fumigation (0.34 and 0.51 ppm) increased the content of the reducing sugars and reduced that of the nonreducing sugars (Malhotra and Sarkar 1979). It was suggested that the increase was due to a breakdown of polysaccharides rich in reducing sugars. Koziol and Jordan (1978) showed that SO_2 exposure of *Phaseolus vulgaris* seedlings caused a reduction in starch content. Reduction in nonstructural total carbohydrates has also been reported following SO_2

exposure of *Ulmus americana* (American elm) seedlings (Constantinidou and Kozlowski 1979).

6.4 Effect on Proline Content

Proline is a part of many proteins and enzymes and has important roles in plants as source of energy and osmoprotectant in stressed conditions (Huber 1984). Proline accumulation in abiotic stress reduces degradation of other proteins (Thomas 1991). Proline accumulation in the cells may happen because of decrease in proline degradation, increase in proline synthesis, and hydrolysis of protein (Fikriye and Omer 2005). The accumulation of proline is related to increase of tolerance against salt and drought stress in many plants (Nayar 2003). Proline acts as free-radical scavenger protecting the plants against damage due to oxidative stress. Higher exposure to air pollutants makes chloroplasts more vulnerable to generate ROS and induces oxidative stress (Woo et al. 2007). Typical environmental stress can cause excess reactive oxygen species (ROS) which are extremely reactive and cytotoxic to all organisms (Pukacha and Pukacha 2000). The deleterious effects of pollutants are caused by the production of ROS in plants, which cause peroxidative destruction of cellular constituents (Tiwari et al. 2006). Hence, higher proline in plants is considered as an indicator of higher stress like osmotic stress (Szekely 2004; Gupta et al. 2015).

6.5 Effect on Enzymatic Activities and Role of Antioxidants

Since higher plants are immobile, they experience environmental stress due to high air pollution load in the atmosphere. The ability of higher plants to scavenge the toxic effects of active oxygen seems to be a very important determinant of their tolerance to these stresses. Antioxidants are the first line of defense against free-radical damage. They are critical for maintaining the optimum health of plant cells. There are several antioxidant enzymes, peptides, and metabolites involved in the scavenging of active oxygen in plants, and their activation are known to increase upon exposure to oxidative stress (Gill and Tuteja 2010). The examples of antioxidant enzymes are superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), monodehrydroascorbate reducatse (MDHAR), dehydroascorbate reductase (DHAR) and glutathione reductase (GR) while antioxidant metabolies include phenolic and nitrogen compounds..

6.5.1 Enzymatic Activity and Peptide Defense

Information on antioxidant levels and the activity of antioxidant-regenerating enzymes are somewhat contradictory; both decreases and increases in the antioxidative capacity of the tissues have been reported (Larson 1988; Foyer and Noctor 2003; Tanou et al. 2009). Such diversification partly arises from the response specificity of a particular plant species and from different experimental conditions (stress treatment, duration of stress, assay procedure, and parameters measured).

6.5.1.1 Catalase and Peroxidase

CATs are tetrameric heme-containing enzymes with the potential to directly dismutate H_2O_2 into H_2O and O_2 and are indispensable for ROS detoxification during stressed conditions (Rao et al. 2006). CAT has one of the highest turnover rates for all enzymes: one molecule of CAT can convert approx. six million molecules of H_2O_2 to H_2O and O_2 per minute. CAT is important in the removal of H2O2 generated in peroxisomes by oxidases involved in β-oxidation of fatty acids, photorespiration, and purine catabolism. The CAT isozymes have been studied extensively in higher plants (Griffiths et al. 1989), e.g., two in *H. vulgare* (Zang et al. 2003), four in *Helianthus annuus* cotyledons (Prasad and Sharma 2004), and as many as 12 isozymes in *Brassica* (Kumar et al. 2007). Srivastava et al. (2010) reported a decrease in CAT activity in *A. doliolum* under NaCl and Cu_2O stress. Simova-Stoilova et al. (2010) reported increased CAT activity in wheat under drought stress but it was higher especially in sensitive varieties. In another study, Sharma and Dubey (2007) reported a decrease in CAT activity in rice seedlings following drought stress. It has also been reported that high light condition increased the CAT activity in *P. asperata* under drought stress (Sharma and Dubey 2007). The UV-B stress also led to a significant increase in CAT activity in *C. auriculata* seedlings (Agrawal 2007). Contrarily, Pan et al. (2006) studied the combined effect of salt and drought stress and found that it decreases the CAT activity in *Glycyrrhiza uralensis* seedlings.

Plant catalases are tetrameric homoproteins that exist as multiple isozymes encoded by nuclear genes. They are located mostly in peroxisomes and glyoxysomes, although a specific isozyme, Cat3, is present in maize mitochondria (Cho and Seo 2005). The catalase of soybean nodules is a typical homotetramer of 220 kDa (Miller et al. 2008). This enzyme may be especially abundant in the peroxisomes of determinate nodules by urease and possibly other oxidases (Tanou et al. 2009). A long-known metalloenzyme, catalase, is one of the most efficient protein catalyses known; it promotes the redox reaction.

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

Hydrogen peroxide itself is not particularly reactive with the most biological precursor for more reactive oxidants such as HO. Although catalase is rather specific for H_2O_2, it reacts with a limited number of organic hydrogen peroxides such as MeOOH, using them to carry out oxidative reactions on the acceptor molecules while simultaneously reducing the peroxidic substrate. Catalase (Cat) is a high-capacity but low-affinity enzyme which destroys hydrogen peroxide. Catalase is a sink for H_2O_2 and that higher-affinity peroxidases, such as ascorbate peroxidase (APX), deal with lower concentrations (Srinivas et al. 2008). The low-catalase plants were more sensitive to stresses such as ozone and high salinity, as well hydrogen peroxide and methyl viologen.

Other important plant enzymes, the peroxidases, also function in this mode. In addition to defense against active oxygen compounds, plant peroxidases have other important cellular roles. However, in different cases endogenous auxin levels are regulated by the enzymes auxin oxidase and peroxidase (Farmer 2007). The activities of some antioxidant enzymes increase during stress treatment, and the types of enzymatic activities that increase are dependent on the form stress imposed. The enzymes whose activities increase during stress treatment may play an important role in defense against that particular stress.

6.5.1.2 Dehydroascorbate Reductase (DHAR)

DHAR is thought to play an important role in the oxidative stress tolerance of plants by regenerating ascorbate from dehydroascorbate (Foyer and Noctor 2003; Bielski et al. 1983). In some plants, DHAR activity has also been reported to increase upon exposure to high temperature, high light intensity, and water deficiency, respectively (Demirevska-Kepova et al. 2006; Zhang et al. 2003; Larson 1988). DHAR regenerates ASH from the oxidized state and regulates the cellular ASH redox state which is crucial for tolerance to various abiotic stresses leading to the production of ROS. It has also been found that DHAR overexpression also enhances plant tolerance against various abiotic stresses. In a study, under Al stress, the role of MDAR or DHAR in ASH regeneration has been studied in transgenic tobacco plants overexpressing *A. thaliana* cytosolic DHAR (DHAR-OX) or MDAR (MDAR-OX). It was found that DHAR-OX-transgenic plants showed higher levels of ASH with or without Al, whereas MDAR-OX plants only showed a higher ASH level in the absence of Al in comparison to WT. Significantly higher levels of ASH and APX in DHAR-OX plants showed better tolerance under Al stress but not MDAR-OX plants. It is clear that plants overexpressing DHAR showed tolerance to Al stress by maintaining a high ASH level (Chen and Gallie 2005). The overexpression of DHAR in tobacco protected the plants against ozone toxicity. Overexpression of DHAR increased salt tolerance in *Arabidopsis* (Ushimaru et al. 2006) and drought and ozone stress tolerance in tobacco (Eltayeb et al. 2006).

6.5.1.3 Ascorbate Reductase (APX) and Glutathione Reductase (GR)

APX is thought to play the most essential role in scavenging ROS and protecting cells in higher plants, algae, euglena, and other organisms. APX is involved in scavenging of H2O2 in water–water and ASH–GSH cycles and utilizes ASH as the electron donor. The APX family consists of at least five different isoforms including thylakoid (tAPX) and glyoxysome membrane forms (gmAPX), as well as chloroplast stromal soluble form (sAPX) and cytosolic form (cAPX) (Smith et al. 2008). APX has a higher affinity for H2O2 (μM range) than CAT and POD (mM range) and it may have a more crucial role in the management of ROS during stress. Enhanced expression of APX in plants has been demonstrated during different stress conditions. Increased leaf APX activity under Cd stress has been reported in *Ceratophyllum demersum* (George et al. 2010), *B. juncea* (Singh et al. 2008), *T. aestivum* (Li et al. 2009), and *V. mungo* (Su and Wu 2004). Noctor and Foyer 1998reported that pretreatment of *O. sativa* seedlings with H2O2 under non-heat shock conditions resulted in an increase in APX activity and protected rice seedlings from subsequent Cd stress. Enhanced activity of APX was also found in salt-stressed *A. doliolum* (Foreman et al. 2003). A significant increase in APX activity was noted under water stress in three cultivars of *P. vulgaris* (Gratao et al. 2005) and *P. asperata* (Flors and Nonell 2006). Sharma and Dubey (2007) found that mild-drought-stressed plants had higher chloroplastic APX activity than control grown plants but the activity declined at the higher level of drought stress. Pekker et al. (2002) studied the expression of cAPX in leaves of de-rooted bean plants in response to iron overload and found that cAPX expression (mRNA and protein) was rapidly induced in response to iron overload. The findings of Koussevitzky et al. (2008) suggest that cytosolic APX1 plays a key role in the protection of plants from a combination of drought and heat stress. Simonovicova et al. (2004) also reported increase in APX activity in *H. vulgare* L. cv. Alfor root tips under Al stress at 72 h.

APX and GR are the major scavengers of hydrogen peroxide in plant cells (Asada 1999) and their activities increase in response to various environmental stressors. In leaves *Arabidopsis thaliana* APX activity increased during exposure of plants to ozone, sulfur dioxide (Radotic et al. 2000) chilling, and UV-B (Koji et al. 2009). Ascorbate peroxidase (APX) and glutathione reductase (GR) activities are increased in water-stressed spinach leaves. In *Arabidopsis* leaves, the decrease in CAT activity when exposed to high temperature, high light intensity, and water deficiency preceded the increase of APX and GR activity. This decrease in CAT activity might trigger the induction of APX and GR activities by reducing the ability of cells to scavenge hydrogen peroxide (Larson 1988).

6.5.2 Metabolic Compounds' Defense

Antioxidants when added in small quantities to materials react rapidly with the free-radical intermediates of an autooxidation chain and stop it from progressing. The primary components of this antioxidant system include carotenoids, ascorbate, glutathione, vitamin E (α-tocopherols) flavonoids, phenolic acids, other phenols, alkaloids, polyamines, chlorophyll derivatives, amino acids and amines, and miscellaneous compounds. It has been recognized that naturally occurring substances too have antioxidant activity including those found in higher plants. Recently, oxygen-containing free radicals in biological systems and their role as causative agents in the etiology of a variety of chronic disorders have been the topics of interests of vegetation. It has also been reported that plants with high levels of antioxidants, whether constitutive or induced, have a greater resistance to such oxidative damage (Edwards et al. 2000; Creissen et al. 1999; Depège et al. 1998; Vierstra et al. 1982; Foyer and Halliwell 1976). A number of studies indicated that the degree of oxidative cellular damage in plants exposed to abiotic stress is controlled by the capacity of antioxidative systems (Sanchez-Rodriguez et al. 2010; Lin et al. 2008; Bartoli et al. 2004; Zhang et al. 2003; Noctor and Foyer 1998).

6.5.2.1 Phenolic Compounds

Phenolics are diverse secondary metabolites (flavonoids, tannins, hydroxycinnamate esters and lignin) abundant in plant tissues (Polidoros and Scandalios 1999). Polyphenols possess ideal structural chemistry for free-radical-scavenging activity, and they have been shown to be more effective antioxidants in vitro than tocopherols and ascorbate. Antioxidative properties of polyphenols arise from their high reactivity as hydrogen or electron donors, from the ability of the polyphenol-derived radical to stabilize and delocalize the unpaired electron (chain-breaking function), and from their ability to chelate transition metal ions (termination of the Fenton reaction) (Ferreira et al. 2002). Another mechanism underlying the antioxidative properties of phenolics is the ability of flavonoids to alter peroxidation kinetics by modification of the lipid-packing order and to decrease fluidity of the membranes (Sandalio and del Rio 1988). These changes could sterically hinder diffusion of free radicals and restrict peroxidative reactions. Moreover, it has been shown recently that phenolic compounds can be involved in the hydrogen peroxide scavenging cascade in plant cells (Harinasut et al. 2003).

6.5.2.2 Nitrogen Compounds

Alkaloids

Increasing evidence from a variety of sources have indicated that the basic nitrogen compounds of higher plants include many representatives that are potent inhibitors of various oxidatives (Gapinska et al. 2008). Caffeine, from the leaves of tea (*Thea sinensis*) and coffee (*Coffea arabica*), was shown to have antioxidative activity (in a linoleic acid oxidation test) comparable to that of butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT). Several alkaloids of various structural types have been found to be potent inhibitors of $^1O_2$. Particularly effective are indole alkaloids such as strychnine and brucine that have a basic nitrogen atom in a rigid, cage-like structure. Such alkaloids appear to be strictly physical quenchers and are not destroyed chemically by the process of quenching. Hence, each molecule of alkaloids could inactivate many molecules of singlet oxygen (Khan et al. 2007).

Polyamines

Polyamines (spermidine and spermine) play a variety of physiological roles in plant growth and development (Singh et al. 2008; Azevedo et al. 1998). They are also potent ROS scavengers and inhibitors of lipid peroxidation (Ali and Alqurainy 2006). Furthermore, exogenous application of polyamines has been shown to protect against various stress conditions such as cold, wilting, pollution, and salinity (Leon et al. 2002). The protection of plants against ozone damage (Wang and Li 2008) by an exogenous supply of polyamines is believed to be caused by the free-radical-scavenging property of the polyamines (Azevedo et al. 1998). Also, the protection of plants against stress damage by an exogenous supply of polyamines is believed to be caused by the free-radical scavengers of the polyamines (Singh et al. 2008).

Amino Acids and Amines

Many amino acids have been tested for their antioxidant activity especially in food-based systems. Antioxidant activity has been claimed for selected amino acids such as arginine, histidine, cysteine, tryptophan, lysine, methionine, and threonine (Gapinska et al. 2008). Certain amino acids may exhibit antioxidant potential under some conditions of temperature or pH or oxygen concentration but have no effect or actually promote oxidation in others. For example, alanine and histidine were reported to inhibit the oxidation of linoleic acid at pH 9.5 and to promote it at pH 7.5 (Gapinska et al. 2008).

6.5.2.3 Other Compounds

Ascorbic Acid

Ascorbic acid (AA) has been known as a biological antioxidant. AA can directly scavenge superoxide, hydroxyl radicals, and singlet oxygen and reduce H_2O_2 to water via ascorbate peroxidase reaction (Noctor and Foyer 1998). High concentrations of ascorbic acid have been reported in many cellular environments, such as the stroma of chloroplasts where its level is 2.3×10^{-3} M. In many qualitative studies, ascorbate has been demonstrated to possess significant antioxidant activity (Ferreira et al. 2002). For example, 10^3 M ascorbate inhibited the photooxidation of a kaempferol by illuminated spinach chloroplasts. Ascorbate reduces two equivalents of O^{-}_{2}-produced H_2O_2 and the triketo derivative dehydroascorbic acid. Ascorbate also reacts with $^1O_2$ at a relatively fast rate (Noctor and Foyer 1998). AA is one of the most studied and powerful antioxidants (Wang and Li 2008; Khan et al. 2007; Larson 1988; Noctor and Foyer 1998). It has been detected in the majority of plant cell types like organelles and in the apoplast. Under physiological conditions AA exists mostly in the reduced form (90 % of the ascorbate pool) in leaves and chloroplasts (Bergmüller et al. 2003) and its intracellular concentrations can build up to a millimolar range (e.g., 20 mM in the cytosol and 20–300 mM in the chloroplast stroma (Foyer and Harbinson 1994)). The ability to donate electrons in a wide range of enzymatic and nonenzymatic reactions makes AA the main ROS-detoxifying compound in the aqueous phase. AA acts as a cofactor of violaxanthin de-epoxidase thus sustaining dissipation of excess excitation energy in chloroplasts (Khan et al. 2007). Recently, Gupta et al. (2015) have reported a higher concentration of AA as an antioxidant which has been attributed to the levels of pollution load and its stress.

6.6 Conclusion

The present chapter highlights the significant effects posed by air pollutants on plant health through biochemical parameters such as chlorophyll, proline content, and other enzymatic activities acting as bioindicators for determining the health of the plant. Moreover, among all the other air pollutants, O_3 and SO_2 affect plant metabolism mostly and can reduce the plant growth. Both morphological and physiological symptoms will be considered while analyzing the health of the plant.

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