Chapter 6
Air Pollution and Its Role in Stress Physiology

Deepti Goyal, Alpa Yadav, and Tanvi Vats

Abstract Environment plays a crucial role in the physiological processes of plants. The numerous biotic and abiotic stresses in the plant habitat trigger complex responses in vital processes like photosynthesis, respiration and stomatal function. In this chapter we discuss the effect of various air pollutants on the stress physiological parameters. These studies are crucial because one of the major responses to plant pollutants is the inhibition of photosynthesis. This inhibition of photosynthesis not only alters the growth pattern and longevity but also changes plant phenology. Besides, assimilation of pollutants into the plant processes ultimately leads to their inclusion in the animal community. All this leads to a vicious cycle wherein the ecological factors suppress plant growth and in turn plants hamper the ecology. In this chapter we have also reviewed and highlighted the mechanistic aspect of the pollutants on the vital physiological parameters. The major pollutants which are emphasized are sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ozone (O_3) while physiological parameters reviewed are stomatal conductance, photosynthesis and respiration and photorespiration. These physiological processes are important parameters in governing growth and health of plants. Because all the natural processes are cyclic in nature, it is pertinent to observe that the stress in plants caused by the pollutants also directly and indirectly affects the human population.

Keywords Environmental stress · Physiological processes · Air pollutants · Mechanistic pathway

---

D. Goyal · A. Yadav · T. Vats (✉)
Gautam Buddha University, Greater Noida, Uttar Pradesh, India
e-mail: tanvi@gbu.ac.in

P. Saxena, A. Srivastava (eds.), *Air Pollution and Environmental Health*,
Environmental Chemistry for a Sustainable World 20,
https://doi.org/10.1007/978-981-15-3481-2_6

6.1 Introduction

The equilibrium between ecosystem stability and socio-economic upgradation is dwindling day by day. The ecosystem stability and its dynamics are key parameters which determine the structure and function of any ecosystem. These parameters are maintained by various biotic and abiotic factors. The factors which negatively affect the agricultural and natural ecosystems include global climate change, deforestation, shifts in land use pattern and air pollution. It is important to note that these factors are interrelated and are not exclusive of each other.

In comparison to other factors, air pollution mostly affects flora and fauna. There are two ways by which airborne pollutants affect ecosystem, directly by toxicity and indirectly by altering soil nutrient availability. It is well established that a single factor does not affect terrestrial ecosystems but a multitude of factors result in chronic exploitation of ecosystem (Taylor et al. 1994). Increased concentrations of CO_2, elevated ultraviolet B (UV-B) radiation, high nitrogen deposition, nutrient deficiencies, drought or temperature extremes are the most emphatic stresses that degrade and hamper the plant characteristics.

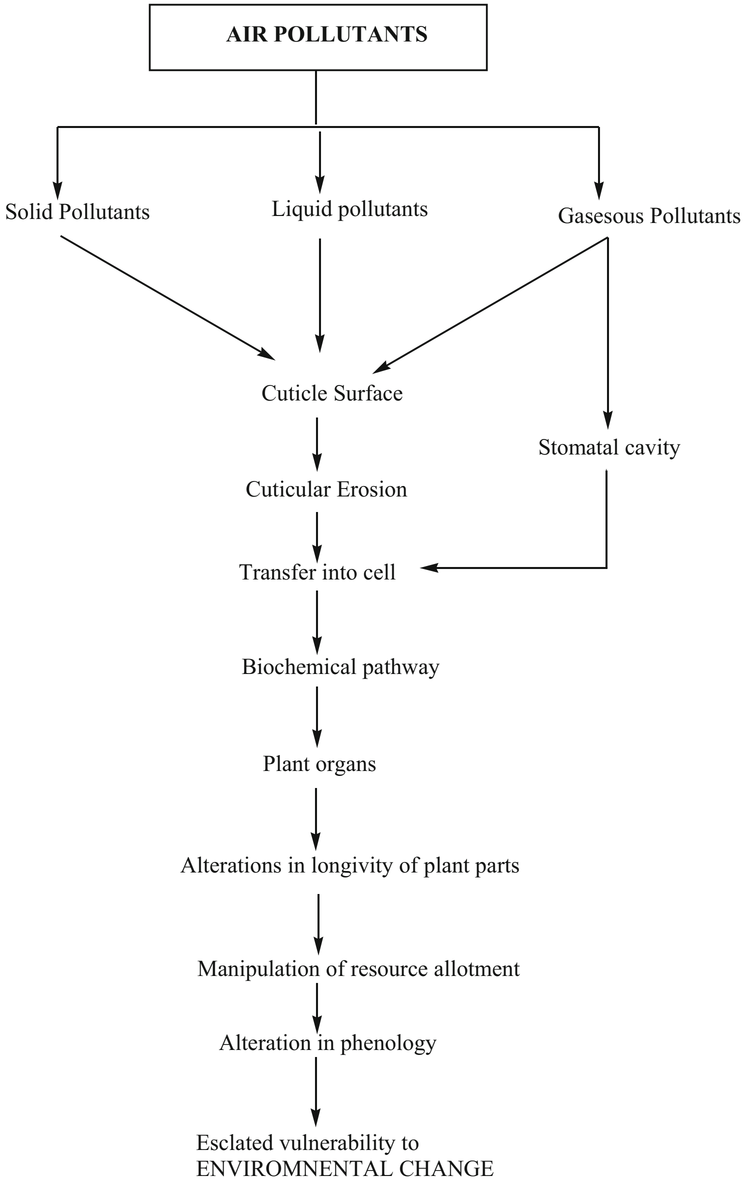
One can safely assume that the air pollutants concern the above-ground parts of the plants in a greater manner than the roots because they are directly exposed to the pollutants. The air pollutants including gaseous pollutants, dust particles and aerosols are adsorbed directly on the large leaf surfaces of vegetation and impact plant function and structure (Mukherjee and Agrawal 2018). The most important plant processes affected by the air quality deterioration are altering of species composition and structure, rate of decomposition, growth and morphology, physiological processes like photosynthesis, respiration, photorespiration and stomatal conductance, leaf functional traits and bioaccumulation of toxic chemicals. The pollutants penetrate from environment into the cells and act as an important carrier in the chain. This is represented in Scheme 6.1.

The pollutants affect the different physiological processes to different extent. The general parameters used to quantify these processes are tabulated in Table 6.1.

Air pollutants are classified as (a) primary pollutants and (b) secondary pollutants. The primary pollutants are the pollutants which are directly released from stationary and mobile sources. Figure 6.1 gives the provenance of primary pollutants.

The primary pollutants undergo chemical changes and reactions to generate secondary pollutants. The formation of secondary pollutants is depicted in Scheme 6.2.

Although there are several pollutants which generate stress in plant physiology, in this chapter we will be discussing only SO_2, NO_x and O_3. The deleterious effects of harmful atmospheric pollutant such as sulphur dioxide, ozone, oxides of nitrogen, peroxyacetyl nitrate, and fluoride on the physiological, morphological and biochemical aspects of flora have been widely reviewed (Baek and Woo 2010). These pollutants mainly disturb the biochemical and physiological processes and cellular structure of the plants (Saxena and Kulshrestha 2016a, b). It is also believed that the pollutants initially disturb the biochemical processes (photosynthesis, respiration,



Scheme 6.1 Pathway of air pollutants: From air to the plant

lipid and protein biosynthesis, etc.), and then attack the ultrastructural level (disorganization of cellular membranes), and cellular level (cell wall, mesophyll and nuclear breakdown) (Saxena and Kulshrestha 2016a, b).

Table 6.1 Quantification of physiological parameters

Process	Tested parameter
Photosynthesis	Chlorophyll fluorescence CO_2 Fixation Gas exchange/stomatal function Photosynthetic functions like ATP production, electron transport, enzymes and metabolites involved in Calvin Cycle
Respiration	Gas exchange Mitochondrial functions Enzymes involved in respiration
Water parameters	Transpiration Stomatal function Water potential Permeability of cuticle
Nutrients	N, P, K, S, Mg, Ca Iron contents
Biorhythms of plants	Electrical conductance in leaves

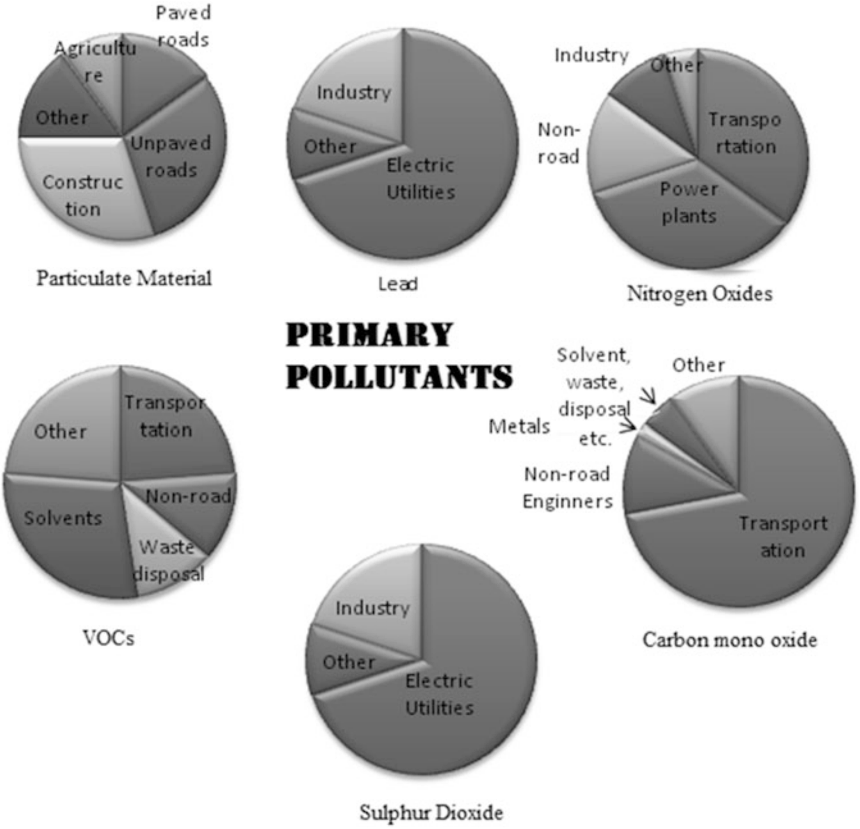
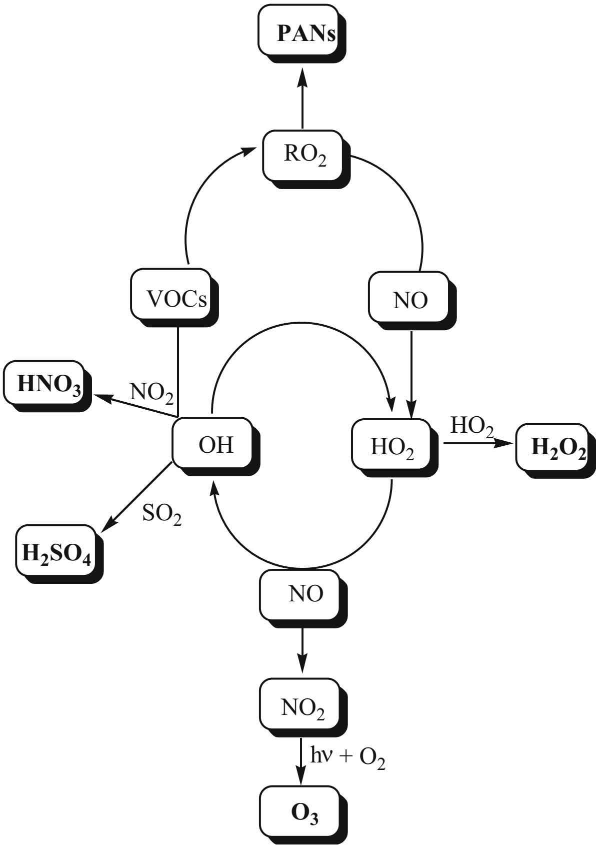


Fig. 6.1 Sources of primary pollutants

Scheme 6.2 Formation of secondary pollutants



6.2 SO_2 and Its Effect on Plant Physiology

One of the most widespread and dangerous air pollutants is sulphur dioxide (SO_2). The main sources of its origin include the burning of sulphur containing fossil fuels and smelting of sulphur containing metals. Another prominent source of SO_2 in winters is crop cultivation using a greenhouse. Greenhouses are meant to keep warm by burning fuels like diesel oil, heavy oil, kerosene and by-product oil, all of which have high sulphur content and their combustion leads to high SO_2 emission (Park et al. 2010).

SO_2 affect the environment both in gaseous as well as aqueous form. In aqueous form, SO_2 in the atmosphere results in acid rain, which is very damaging for plants, trees and forests. Acid rain leaches essential nutrients like calcium and magnesium from soil, which results in the plantation getting more prone to infection and damage by cold weather and insects. Not only this, aluminium also is removed from the soils which hinders the water up-taking capacity of the trees. Besides, acid rain destroys the outer coating of leaves, hampering the photosynthesis. In human beings even the trace amount of acid particles leads to respiratory problems like asthma, chronic bronchitis and pneumonia. In the aquatic system, increase in acid content reduces the pH of water bodies leading to fish mortality.

In gaseous form, SO_2 affects the human health by entering through the respiratory tract. It causes irritation in the skin, and mucous membranes of eyes, nose, throat and lungs, which is responsible for throat irritation, coughing, wheezing and breathing difficulty. High concentration of SO_2 can affect lung function, worsen asthma attacks and heart disease in sensitive groups.

Apart from living organisms, SO_2 is equally hazardous to man-made materials. It severely damages a variety of carbonate-containing building materials like limestone, marble and mortar.

SO_2 attacks on leather causing disintegration of leather goods. In case of metals though aluminium is almost noble to SO_2 attack, other metals like iron and steel get highly corroded by it. Various other materials like paper, wool, cotton etc. also deteriorate on SO_2 exposure leading to embrittlement and eventual loss of strength (Saxena et al. 2019).

Sulphur being a key constituent of amino acids, proteins and a few vitamins, is essential for plant metabolism. A low concentration of SO_2 is necessary for physiological growth of plants (Darrall 1989), especially in sulphur-deficient plants in which sulphate might be metabolized to sulphur to fulfill nutrition in plants (DeKok 1990). But at higher concentration of SO_2, general disruption of photosynthesis, respiration and other fundamental cellular processes can occur. This can be understood as a chain of events wherein an increased uptake of SO_2 leads to a buildup of sulphites and sulphates which in turn are cytotoxic and stop the growth and productivity of plants (Darrall 1989; Agrawal and Verma 1997). SO_2 toxicity has a rather adverse effect on plant pigments and therefore SO_2 exposure reduces photosynthetic activities. SO_2 exposure also leads to tissue damage and the most affected areas are stomata, cell membranes and leaves while the most affected functions are transpiration, membrane transport and permeability. These all, in unison leads to reduced plant growth and a diminished yield (Crittenden and Read 1978; Unsworth and Ormrod 1982).

SO_2 uptake can be both from root as well as shoot system. Sulphur is taken in the form of sulphate ions by the root and is assimilated into organic sulphur compounds. These sulphur compounds are employed in various biochemical processes and thus eventually become a part and parcel of the ecosystem (Omasa et al. 2002; De Kok et al. 2002).

The SO_2 uptake by the plant's shoot system can be shown as in the schematic representation in Fig. 6.2.

Plants do not show a uniformity in responses to SO_2 exposure due to their different absorption efficiency towards the gas as well as their capability to remove the excessive sulphur and detoxify the pollutants. Once the SO_2 enters in the plant through leaf, it dissolves in the moisture present in mesophyll cell and converts into sulphite and bisulphate (Kulshrestha and Saxena 2016). These toxic elements (sulphite and bisulphate) are then translocated to other parts of the plant. Several studies have been done during the past two decades to understand the effect of SO_2

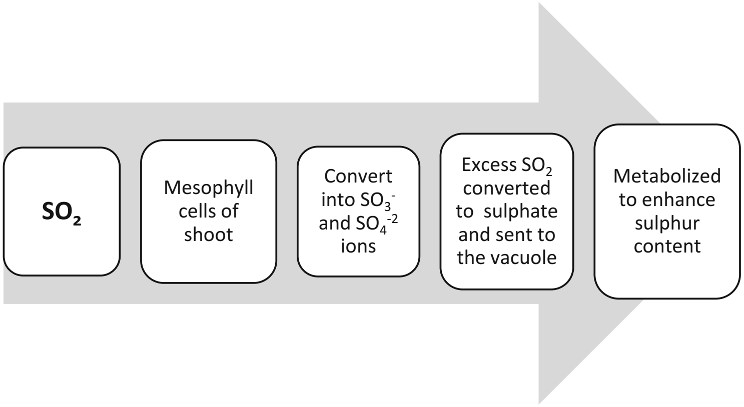


Fig. 6.2 SO_2 uptake by shoot of plants

Table 6.2 Classification of plants on the basis of extent of SO_2 exposure effects

Type of Plants	Species	Exposure effect
Herbs	Wheat, Barley, Pea, Beet, Bean, Carrot, Chilli, Petunea, Oat, Potato, Tobaco.	Immediate deterioration
	Croton, Opuntia, Nerium, Vinca	Slow, chronic effect
Shrubs and Trees	Mango, Arjun, Sisso, Jamun	Immediate deterioration
	Neem, Banyan, Bougainvillea, Chatim, Jarul, Sims, Pongamia pinnata	Slow, chronic effect

on various plants species. On that basis, a list of acute and chronic effects on plants is given in Table 6.2.

Exposure to SO_2 at even low concentrations may have several damaging effects on plants, such as:

- Reduction in photosynthetic and transpiration rate
- Increase in respiration rate
- Increase in stomatal conductance
- Reduction in chlorophyll content
- Membrane lipid peroxidation

6.2.1 SO_2 and Its Effect on Stomata

The pollutants enter into the plant through the leaf having abundant stomata on its surface. The response of stomata towards SO_2 depends upon species of plant, concentration of SO_2, plant age and environmental conditions. It is also found that exposure time of SO_2 affects opening and closing of stomata (Saxena and Sonwani 2019a, b, c). When a leaf gets exposed to SO_2 for a short time it causes stomatal opening, while for long-time exposure it causes stomatal closing (Abeyratne and Ileperuma 2006; Raschk 1975; Rao et al. 1983; Verma and Singh 2006; Robinson et al. 1998; Bytnerowicz et al. 2007). The effect of SO_2 concentration on stomatal opening is different in different plants (Biggs and Davis 1980). In one plant species it can cause stomatal opening while in another stomatal closing (Mudd 1975).

The SO_2 uptake depends upon the pore size and quantity of stomata, which affect the turgidity of guard cells. Long-term exposure of high concentration of SO_2 reduces the ability of guard cells to collect sulphur and open or close the stomata (Guderian 2012; Knabe 1976), which then alters the fabrication and supply of photosynthates (Khan and Khan 1993). There is decrease in stomata abundance (Olszyk and Tibbitts 1981; Kumari and Prakash 2015; Koziol and Whatley 2016), which is a necessary action to avoid entrance of high-level SO_2 into the leaf, due to which damaging of plant tissues can occur (Kumari and Prakash 2015).

Abeyrante and Ileperuma (2006) have studied the effect of SO_2 on stomatal pore width of *Argyreia populifolia* leaves at the three sampling sites of the Peradeniya University Park, Sri Lanka. Sampling site 1 was reported at high SO_2 concentration and other two locations (sampling site 2 and 3) were with moderate SO_2 concentration. A reduction (almost 50%) in the values of both length and width of stomatal pore were observed at sampling site number 1, whereas sampling sites 2 and 3 gave almost identical values of pore length and width (Abeyratne and Ileperuma 2006).

A decrease in cellular pH responsible for stomatal closure is also reported due to sulphur dioxide fumigation. This is due to the fact that SO_2 reacts with cellular water content and produces sulphuric acid according to the following reaction:

$$\left(SO_2 + H_2O \rightarrow [SO_2 \cdot H_2O] \rightarrow HSO_3{}^{-} + H^+ \rightarrow SO_3{}^{2-} + 2H^+\right)$$

This may lead to inhibition of K^+ pump, responsible for stomatal closure (Dhir 2016) which thus affects the photosynthetic yield. Another reason for closing of stomata is the presence of abscisic acid (AbA) hormone in the leaf which is produced due to exposure to SO_2 (Hu et al. 2014). In case of high SO_2 exposure, stomatal conductance also gets reduced which affect the physiological processes of photosynthesis (Choi et al. 2014a; Liu et al. 2017).

Majemik and Mansfield (1971) found that SO2 does not affect the normal diurnal cycle of opening and closing of stomata, but increases the apertures during the day in plants (Majernik and Mansfield 1971). Similar results were found in another study on a plant species *Vicia faba*. The stomatal conductance was increased by 20–25% on exposure to low SO_2 concentrations (Black and Black 1979). This enhanced opening was responsible for damage of epidermal cells adjoining to the stomata.

In another study stomatal abundance and increase in epidermal cells in leaves of *Azadirachta indica* and *Polyalthia longifolia* (Pal et al. 2000), *Cassia siamea* (Aggarwal 2000), and *Nyctanthes arbortristis*, *Quisqualis indica* and *Terminalia arjuna* (Rai and Kulshreshtha 2006) on SO_2 exposure have been found. Along with this, reduced stomata and epidermal cells size with exposure to SO_2 has also been found from other researchers' works (Aggarwal 2000; Kaur 2004; Dineva 2006). This may be due to inhibited cell elongation, leaf area and increase in cell occurrence (Rai and Kulshreshtha 2006).

6.2.2 SO_2 and Its Effect on Photosynthesis

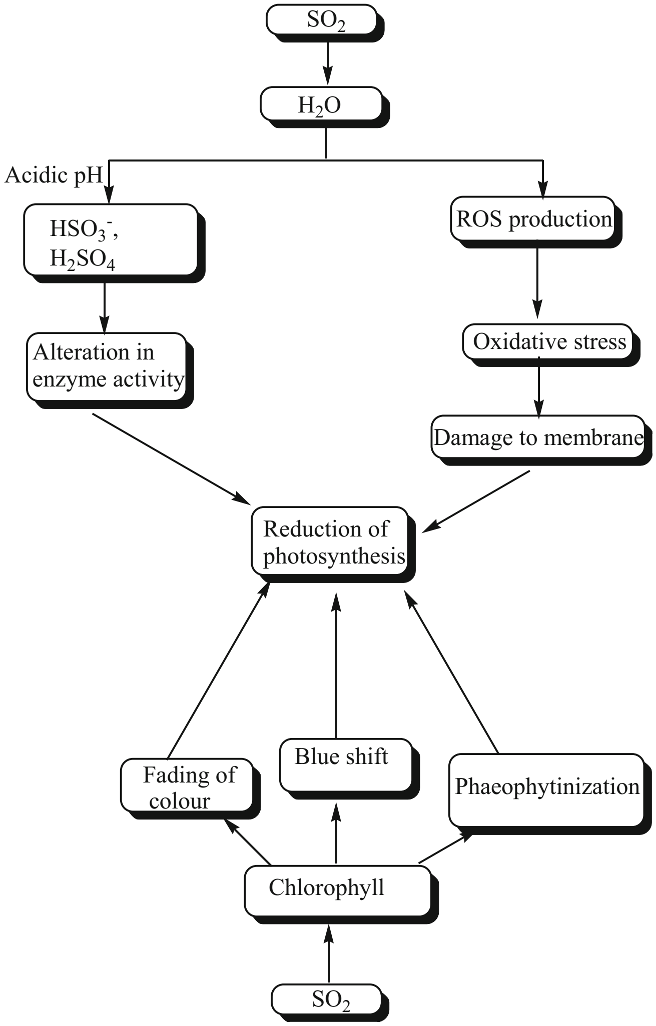
The vital physiological process of photosynthesis is highly sensitive to SO_2 concentration and duration of exposure (Saxena and Sonwani 2020). In various studies it was found that short-time exposure to low SO_2 concentrations generally stimulates photosynthesis, whereas long-time exposure even at low concentration of SO_2 was responsible for inhibition of photosynthesis (Gheorghe and Ion 2011).

SO_2 destroys electron transport between photosystems, which decreases the rate of electron transport throughout the chain. The overall result of this is the reduced rate of photosynthesis (Gheorghe and Ion 2011). Another reason for reduced photosynthetic rate on SO_2 exposure may be due to reduced amount of chlorophyll (Aminifar and Ramroudi 2014; Hetherington and Woodward 2003). SO_2 exposure effect on chlorophyll can be trifurcated in three ways:

1. Fading of chlorophyll color
2. Phaeophytinization wherein chlorophyll molecules get degraded to phaeophytin (less active molecule))
3. Blue shift in pigment spectrum of lichens (Hetherington and Woodward 2003)

In a study on oak species, *Gracia* and coworkers found that decrease in photosynthetic rate could be due to reduction in protein contents and decreased carboxylation efficiency resulting in a reduced CO_2 uptake besides the chlorophyll factors (Farage et al. 1991). Because of its acidifying properties, a very high concentration of CO_2 acts as inhibitor. Reduction in leaf area and CO_2-induced shift in the timing of the leaf ontogenetic processes (Miller et al. 1997; Rey and Jarvis 1998) may also be the additional factors for reduced photosynthesis. Similar results were found for rice and spinach.

SO_2 deteriorates the height and girth of plant axis. It is well documented in literature that the photochemical efficiency of photosystem II in a healthy leaf ranges between 0.74 to 0.85, which gets drastically reduced when exposed to SO_2 (Choi et al. 2014b; Seyyednejad and Koochak 2011a; Lichtenthaler et al. 2005; Sobrado 2011). Furthermore, SO_2 exposure also inhibits the activity of essential Calvin cycle enzymes like Fructose bisphosphatase and Ribulose bisphosphate carboxylase (Chung et al. 2011). Reduction in the total chlorophyll content upon exposure to the gaseous SO_2 has also been documented in the literature. This may be due to the negative impact of SO_2 on chlorophyll metabolism (Choi et al. 2014b; Seyyednejad and Koochak 2011b). In addition to this, Seyyednejad and Koochak demonstrated that in *Prosopis juliflora*, the concentration of photosynthesis pigments like chlorophyll carotenoids Fwas decreased when leaf was exposed to SO_2. The reason behind



Scheme 6.3 Reduction of photosynthesis on SO_2 exposure

this is the deposition of suspended particulate on leaf surface (Seyyednejad and Koochak 2011b).

The reduction in photosynthesis on SO_2 exposure is represented in Scheme 6.3.

6.2.3 *SO_2 and Its Effect on Respiration and Photorespiration*

Respiration also called dark respiration is a metabolic pathway which produces energy-rich molecules by the breaking of larger molecules like carbohydrates

(Sonwani and Saxena 2016). In general, the rate of respiration increases when a plant is exposed to gaseous pollutants viz. SO_2, O_3, HF and NO_2. Some researchers have found that the rate of dark respiration increased when exposed to 35–380 ppb concentration of sulphur dioxide, while some other haves reported no change at 20–4000 ppb concentration of SO_2 (either short term, i.e., less than 8 h or long term, i.e., more than 1 day). Black and Unsworth (1979) studied the effect of SO_2 on one species, *Vicia faba* and they observed that the increase in the rate of dark respiration was not affected by the SO_2 concentration from 35 to 175 ppb (Black and Unsworth 1979). In addition to this, SO_2 exposure also affects the respiration rate in lichens and bryophytes. In some cases when certain lichens such as *C. impexa, Hypogymnia physodes, and Usnea fragiliscence* were exposed to a low concentration of aqueous solution of SO_2 with 23–27 ppm concentration, a decrease in rate of respiration was observed. On the basis of these findings, we can conclude that the change in respiration rate mainly depends on the concentration of SO_2.

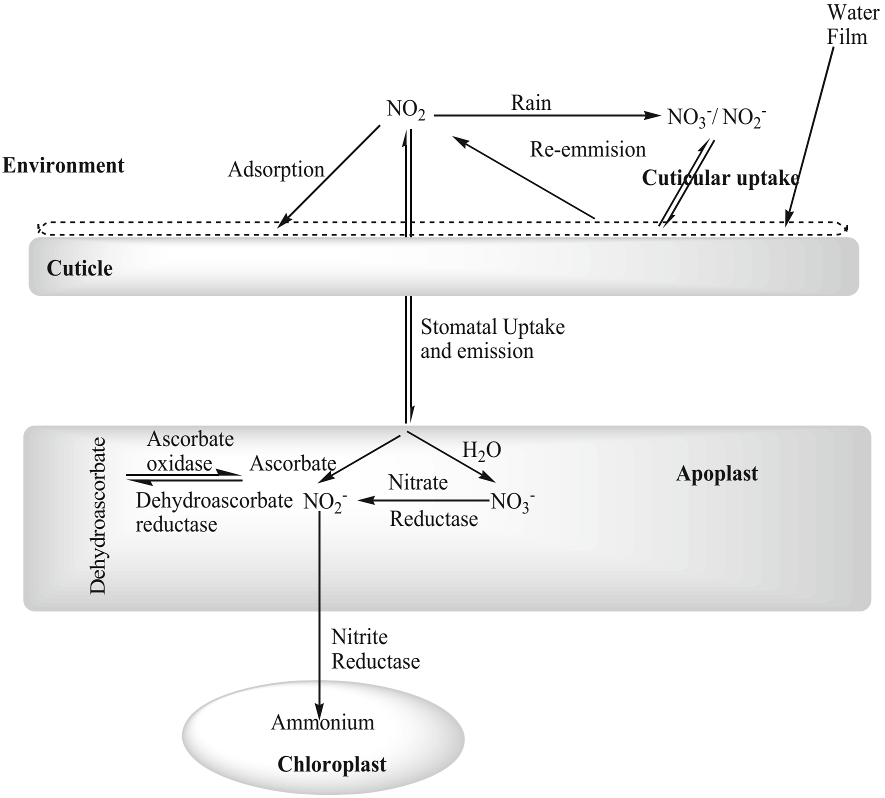
Photorespiration, also known as light respiration, occurs in chlorophyll tissues of plants in the presence of light and at higher O_2 concentration (Saxena and Naik 2018). It is a distinguished aspect of C_3 plants and essentially absent in C_4 plants. Generally, air pollutant has little effect on photorespiration. At high SO_2 concentration (1000 ppb), inhibition in photorespiration occurred. The effect of sulphur dioxide on photorespiration is also found in higher plants, due to which their productivity is greatly influenced (Black 1984).

6.3 NO_X and Its Effect on Plant Physiology

NOx, a primary air pollutant, enters into the environment through fuel combustion processes. The increase in automobile exhaust emissions from industrialized areas is responsible for increase in NO_x concentration (Munzi et al. 2009; Hu et al. 2015; Hultengren et al. 2004). NO_x is mainly composed of NO (>90%) and NO_2, which can covert into each other in sunlight and in the presence of some gases like O_3. NO_2 also releases some harmful pollutants in the environment like O_3 and particulate matters (Rahmat et al. 2013; Bermejo-Orduna et al. 2014; Marais et al. 2017).

Research studies have adopted two assumptions for plant response to NO_2 exposure. In one assumption it is proposed that NO_2 can produce nitrogenous compounds by its metabolism and incorporation in the nitrate assimilation pathway, which does not cause any visible injury (Stulen et al. 1998). Some other studies anticipated that the majority of the plants show evidence of fewer amounts of NO_2 (Middleton et al. 1958).

On the basis of a general hypothesis, it is believed that when NO_2 is present in high concentration it can cause extreme accumulations of NO_2^- (Okano and Totsuka 1986) and cell acidification (Schmutz et al. 1995). Due to this, deterioration of plant growth occurs by production of reactive oxygen species (ROS) and inhibition of absorption of N (Sonwani and Maurya 2018). On the other hand, some different physiological responses were obtained on NO_2 exposure. Therefore, there is a



Scheme 6.4 Assimilation of NO_2 into chloroplast via stomata

disagreement on the effects of NO_2 exposure on plants and a united conclusion has not been reached.

Various environmental factors (Gebler et al. 2000; Chaparro-Suarez et al. 2006), stomatal dimension and conductance (Chaparro-Suarez et al. 2011; Breuninger et al. 2013) affect the foliar NO_2 uptake. NO_x is a free radical gas which transfers electrons crossways biological membranes due to which reactive oxygen species (ROS), a by-product of other biological reactions is generated (Xu et al. 2010). The NO_2 uptake in plants may be done directly through the stomata and/or through roots. The assimilation of NO_2 into chloroplast via stomatal route is given in Scheme 6.4.

The mechanism of absorption of gaseous NO_2 into leaf through stomata is proposed in two ways.

1. Either it is disproportionated to nitrate and nitrite in the apoplast

$$NO_2 + H_2O \rightarrow H^+ + NO_3^- + NO_2^-$$

2. Or absorbed in leaf apoplast by ascorbate

$$\mathrm{Asc} - \mathrm{OH} + \mathrm{NO_2} \rightarrow \mathrm{Asc} - \mathrm{O} + \mathrm{H^+NO_2^-}$$

In apoplast NO_2^- is converted to NO_3^- where it is metabolized by enzyme nitrate reductase (NaR) producing NO_2 where it is taken up from the apoplast and then transported into the chloroplast (Eller et al. 2011). At high concentration NO_2 is capable of being stimulated upon nitrate reductase and responsible for more intense reduction of nitrite to ammonia and amino acids (Erisman et al. 2007)

It is pertinent to note that there are relatively few reports on effect of NO_x on plant physiology, perhaps because of the fact that it is less toxic as compared to SO_2. It is also found that the effects of NO_x are most prominent when it is combined with SO_2 (Carlson 1983; Whitmore and Mansfield 1983; Freer-Smith 1985). In uncombined form NO_x is damaging only at high concentrations (Reinert et al. 1982). Furthermore, NO has less toxic effect than NO_2, which may be attributed to its less solubility in water which in turn leads to lower uptake (Mansfield and Freer-Smith 1981). Another reason could be that NO gets easily converted to NO_2; therefore, the effects of NO are difficult to quantify. Nowadays, the concentration of NO_2 is steadily increasing and in some countries it exceeds the concentration of SO_2 (Lane and Bell 1984a; Martn and Barber 1984). It is also found that in rural areas the concentration of NO and NO_2 may be same, but in urban areas the NO concentration is high (Lane and Bell 1984b).

6.3.1 *Effect of NO_2 on Stomatal Conductance*

On foliar surface, the flow of NO_2 into the leaf has been a matter of intense discussion (Rogers et al. 1979; Fatima et al. 2018; Thoene et al. 1996; Teklemariam and Sparks 2006; Gebler et al. 2000). The exhaustive studies lead to the conclusion that the NO_2 deposition was much more than the cuticular deposition through stomatal contribution to the total leaf. Some studies suggested that cuticular contribution is upto 5% in most of the cases (Saxena and Sonwani 2019a, b, c). In 1900, Wellburn introduced that at 140 ppb NO_2 concentration, deposition through the stomata was higher than the deposition on the cuticle (Wellburn 1990).

The NO_2 uptake process is highly influenced by the water films. It is proposed that absorption of water occurs through water film of plant surface. High humidity leads to deposition of water films on the leaf surface which in turn serves as sink for atmospheric NO_2 (Burkhard and Eiden 1994). Some researchers suggested that NO_2 consumption is solely depended on stomatal opening and that cuticular expulsion was entirely ruled out.

The stomatal dynamics as well as stomata-related physiological and biochemical processes are affected by the corrosive and oxidizing attributes of NO_2 (Takagi and Gyokusen 2004; Mazarura 2012). In a recent study on populous trees, Yanbo Hu et al. (2015) showed that NO_2 gas has remarkable adverse influence on stomata connected with physiological processes of *Populus alba* and *P. berolinensis* leaves (Hu et al. 2015).

6.3.2 Effect of NO_x on Photosynthesis

Reduced photosynthesis is observed in various plants when exposed to gaseous NO_x, even at concentrations that do not produce visible injury (Hill and Bennett 1970; Capron and Mansfield 1976). It was also been observed that the effect of NO was much more rapid than the effect of NO_2 (Hill and Bennett 1970). In another study it was found that NO_2 concentration and exposure time were responsible for reduced photosynthesis (Srivastava et al. 1975). The effect of NO_x on photosynthesis is much less than other pollutants. Short-term exposure (< 8 h) of NO_2 between 500 to 700 ppb and continuing exposure (⍰20-h period) at 250 ppb, can cause changes in photosynthetic rate (Hill and Bennett 1970; Capron and Mansfield 1976). In variation to above, nitric oxide disrupted four times like NO_x gets reduced to dioxide at 1000 ppb in a 4d ventilation of a variety of greenhouse plants (Saxe and Murali 1989).

Reduction of NO_2, into nitrite and ammonia was found when NO_2 entered into the plant, by reduced ferredoxin or by reduced nicotinamide adenine dinucleotide phosphate (NADPH) Reduction of NO_2 could be explained in the rate of photosynthesis as on the basis of presence of NADPH for nitrite reduction and absorb carbon in the chloroplast. Furthermore, the acidic behaviour of NO_2 can change the electron movement and photophosphorylation. As photoelectron systems are associated with chloroplast membranes, any changes in their structures would influence activities of the photosystems (Hill and Bennett 1970; Srivastava et al. 1975).

NO_2 exposure is also responsible for swelling of chloroplast membranes (Wellburn 1990). This may result if NO_2 is reduced into ammonia, which is not rapidly incorporated into amino-forms and thus responsible for inhibition of photosynthesis by uncoupling electron transport (Avron 1960). Similarly, in some lichen species, reduced chlorophyll content was observed on NO_2 fumigation (Nash 1976). The inhibition in pigment synthesis on NO_2 exposure is also documented in the literature. This may be due to inhibition in photooxidative processes, which may affect the synthesis of chlorosis. Moreover, rise in percentage of chlorophyll by about 10% occurred in *Pisum sativum* with NO_2 exposure in some other study (Horsman and Wellburn 1975).

In some investigations, researchers found the effects of NO on photosynthesis rate of glasshouse crops, particularly the tomato (*Lycopersicon esculentum*). From the results, they concluded that in controlled fumigation, some NO is oxidized to NO_2. So, it is difficult to interpret the effect of NO on photosynthesis since atmosphere will contain a blend of the oxides (Saxena and Sonwani 2019a, b, c). It is also found that it is not clear that which oxide is the more toxic. In a latest research it has been reported that with NO rate of photosynthesis decreases rapidly as compared to NO_2 (Hill and Bennett 1970).

In comparison with the effect of NO_2 alone, spraying with a mixture of NO_2 and SO_2 has been found to show adverse effect on the rate of photosynthesis. At lower concentration (200-250 ppb), the combined effect of these gases on inhibition of net photosynthesis was much higher than with these gases individually. The study was done on various plant species like *Medicago sativa*, *alfalfa*, and *Glyeine max* (Carlson 1983). Thus, nitrogen dioxide and nitric oxide had reported good results only at high concentrations, that is 500–700 ppb and above, but when it combines with sulphur dioxide, effect of inhibition is high than that single gas.

6.3.3 Effect of NO_2 on Respiration and Photorespiration

Respiration is an important process for plant metabolism and growth, and also for rebuild and neutralization of the toxics (Koziol and Whatley 2016). Currently, there is no compatible way to recognize the effects of nitrogen dioxide on respiration. At concentrations between 40 and 400 ppb of nitrogen dioxide or nitric oxide, no effect was found on inhibition and stimulation, but high concentrations of these two gases, that is 1000–7000 ppb, showed effective behaviour for the same. Bengtson et al. (1982) have been studying the effect of NO and NO_2 on *Pinus sylvestris* at 40–400 ppb for 6 h. They found ineffective behaviour of NO_x on respiration in the absence of light at this concentration and time. In another study on pot plant cultivators, it was demonstrated that on 1000 ppb of NO fumigation for 4 h, there was inhibition in one cultivator (5.1%), while under similar conditions of NO_2 fumigation, there was an increase in two cultivators (8.2%) (Grennfelt et al. 1983).

Sabaratnam and Gupta investigated the effect of NO_2 on one-month mature soybean plants. The plants were treated with different specified limits of NO_2 concentrations from 0.1 μl liter^{-1} to 0.5 μl liter^{-1} for 5 days (7 hour per day), under controlled environment. The results showed that above the concentration from 0.3 μl liter^{-1} of NO_2, the rate of dark respiration was rapidly increased; this may be due to elevated activity of cellular physiology to metabolize the pollutant to non-toxic forms caused by NO_2 (Sabaratnam and Gupta 1988).

Oxides of nitrogen (NO and NO_2) are sometimes referred to as total reactive nitrogen oxides, which includes NO, NO_2, nitrous oxide (N_2O), nitric acid (HNO_3), nitrous acid (HNO_2), peroxyacetyl nitrate (PAN), organic nitrates, and other forms of oxidized nitrogen (Weller et al. 2002). Nitric oxide free radical is unstable and not easily deposited to surfaces in remarkable amounts (Horii et al. 2004). NOx species, mainly NO_2 a free radical, and a potent oxidant is related to deposition studies. It is principal constituent of urban air pollution (Jacobson et al. 2004). In atmosphere NO_2 is produced by the oxidation of nitric oxide (NO) which is formed by the oxidation of N_2 at high temperatures during combustion processes in energy production, burning of fossil fuels in automobiles by tropospheric ozone (O_3). O_3

rapidly converted NO to $NO_2$by oxidation process. NO_2 levels are used as an overall indicator of the atmospheric NOx status for U.S. EPA.

6.4 O_3 and Its Effect on Plant Physiology

The troposphere ozone is formed under sunlight via chain of chemical reactions with different intermediates of nitrogen oxides (NOx) and volatile organic compounds. Depending upon where it is found, ozone can be good or adverse. Good ozone forms a safety layer to shield us from harmful UV rays of sun (Sonwani and Kulshrestha 2016). The process of formation of ozone occurs naturally in upper atmosphere. Unfavourable ozone is formed in lower atmosphere, that is troposphere, where pollutants come in this level from man-made pollutants and from chemical reaction occuring in the presence of sunlight. Ozone at lower level is a destructive air pollutant. Ozone is a secondary pollutant formed in the presence of sunlight with nitrogen oxides (NOx), which comes mainly from automobiles and biomass burning, in the presence of volatile organic compounds as shown in Fig. 6.2.

Ozone in tropospheric region considered as a highly reactive pollutant, which produces adverse effects on plant development (Betzelberger et al. 2012; Wilkinson et al. 2012). Ozone goes into the plant through the stomata and reacts with different compounds connected with cell walls and membranes. The effect of ozone on plant development is determined with the concentration of ozone and the exposure time. Long-time exposures of ozone pollution on plant can change plant physiology, leading to changes in plant activities that can ultimately affect climate and atmospheric chemistry via transpiration, biogenic emissions, dry deposition, etc. Reduction of photosynthesis by dry deposition onto leaves is a major sink for ozone, but ozone exposure is also detrimental for the following phenomenon:

- Plant tissues → impact on ecosystems and crops.
- Reduces stomatal conductance (damage).
- Surface ozone is a major air pollutant (causing ~0.7 M deaths/year).
- Reduces leaf Area Index (damage).
- Toxicity of ozone on plants shows symptoms comprising foliar damage, premature leaf erosion, decrease in growth and limited belowground of proportion of carbon.

The effect of O_3 exposure on plants and their eventual influence on ecosystem is given in Fig. 6.3.

6.4.1 Effects of Ozone Stress on Stomatal Conductance

The mechanistic pathway of ozone influence on stomatal conductance is by injuring the epidermal cells and causing them to break and open wide (Sonwani et al. 2016).

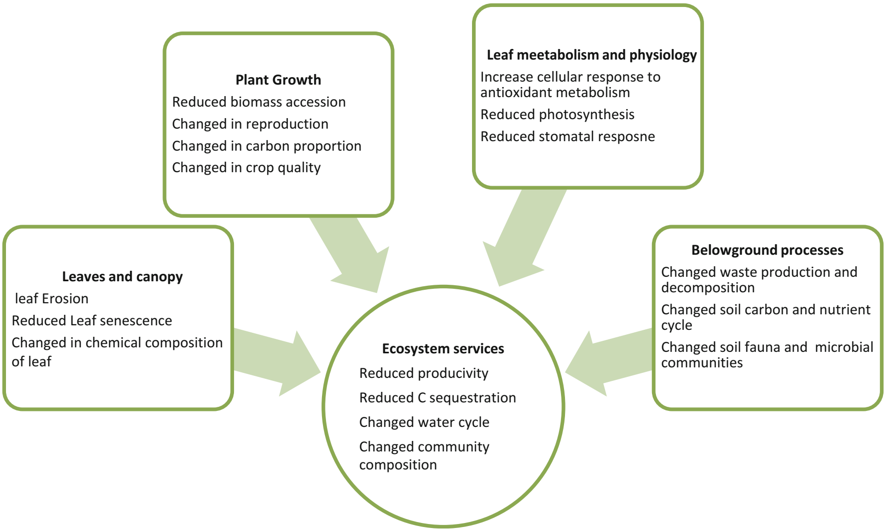


Fig. 6.3 Effect of O_3 exposure on plant ecosystem

This leads to closing of stomata and decrease in stomatal conductance. Besides stomatal functions, ozone exposure damages photosynthetic tissues and reduces photosynthetic pigments (Saxena et al. 2017).

The O_3 exposure goes hand in hand with the weather conditions. Stagnant weather conditions limit the dose of ozone absorption. Also, it is interesting to note that low humidity leads to low stomatal conductance.

On studying the effect of O_3 exposure on *B. nigra*, it was observed that even a short-term exposure reduced stomatal conductance and leaf transpiration, resulting in low quantities of intracellular CO_2. A long-term exposure, on the other hand, increased intracellular CO_2. The bleaching and chlorosis of the leaves was observed and was attributed to increase in CO_2 concentration (Paoletti and Grulke 2005).

O_3 stress also brings about the appearance of *MYB44* gene. This gene takes a major role in responses to abioitc and biotic stress. It is believed that the appearance of *MYB44* elevates tolerance to low rainfall, by improving stomatal closure, leaf senescence and ROS scavenging. This is indicative of the extreme stress in plants because of O_3 exposure, matching draught- or famine-like situation (Baldoni et al. 2015; Jung et al. 2008; Jaradat et al. 2013).

6.4.2 *Effects of Ozone on Photosynthesis*

The plants exposure to ozone is the main internal factor which influences the rate of photosynthesis through multiple ways. The change in the photosynthetic rate on O_3 exposure depends on variety of plant, leaf age, O_3 concentration and exposure time, and other environmental conditions (Moldau et al. 1993; Dizengremel 2001). Along with these factors, reduced carboxylation efficiency is also found as an important factor for reduced photosynthesis (Pell et al. 1992, 1994; Farage and Long 1999). Due to the strong oxidizing nature of O_3, it significantly reduces photosynthesis and therefore responsible for reduction in ribulose 1.5-bisphosphate carboxylase/oxygenase (Rubisco) activity (Dizengremel 2001), and decreases the CO_2 uptake of leaf (Farage et al. 1991).

Many researchers have found that ozone generally decreases photosynthetic rate of plants (Bagard et al. 2008) and also reduces plant productivity (Dizengremel 2001). Along with this, O_3 is also responsible for chlorophyll degradation and early leaf ageing (Bergmann et al. 1999; Ranieri et al. 2001). In a similar study on soyabean leaves, a reduction in chloroplast content, photolysis and oxygen of water was found when soyabean leaves was exposed to O_3. This is due to the fact that this increased ozone accounts for reduced phosphorylation (Julia and Kangasjärvi 2015). Moreover, persistent O_3 exposure above 40 nL L^{-1} concentration produces reactive oxygen species (ROS) which prevent uptake of O_3 through leaf by closing the stomata (Bergmann et al. 1999; Ranieri et al. 2001; Vahisalu et al. 2010).

Many researchers have studied the effect of concentrations and exposure time of O_3 on photosynthesis to know the effect of threshold concentrations and dose–response relationships. Some studies show reduction in photosynthesis when short-term exposed at 100 ppb, while others show reductions at 200–500 ppb. On long-term exposure to O_3 (<1 d) at 35–45 ppb also effects photosynthesis in crop plants (Reich and Amundson 1985).

Some studies reveal that the effect of O_3 exposure on tree species was only at higher concentrations or at long-time exposure than in herbaceous plants (Barnes 1972). Other species were more tolerant. In some cases, it was established that the O_3 exposure affects the newly enlarged foliage much more than mature foliage. It was evident when newly enlarged foliage of white pine was exposed to 150 ppb of O_3 for 19 days; it did not survive for 77 days long exposure.

The effect of O_3 on photosynthetic rate in another plant species was calculated at 85 and 125 ppb ozone exposure, and it was found that this affect the quantum yield, light dispersion value and the light damages point of the photosynthesis responses.

The O_3 exposure also affects photosystem I and II in plants. When *Spinacia oleracea* chloroplast was exposed to O_3, the electron transport system in both photosystems was inhibited; however, photosystem I was found much more effected than photosystem II (Reich and Amundson 1985; Coulson and Robert 1974). This may be due to the reduced photophosphorylation which resulted from reduction in electron transport. O_3 affected the chlorophyll content of the treated plants (Leffler and Cherry 1974). In another research a strong connection was observed between chlorophyllioss and visible necrosis (Knudson et al. 1977). The reduction comparison of Chlorophyll a to Chlorophyll b was also observed on O_3 exposure. This may be due to the fact that chlorophyll a has much more affinity towards O_3 than chlorophyll b.

Schreiber et al. (1978) reported the effect of O_3 on the fluorescence characteristics in *Phaseolus vulgaris*. The results showed that a long-time exposure at low concentration was much more injurious than a short-time exposure at high concentration. On this basis it was concluded that the effect of O3 on fluorescence is due to its action on the donor site of Photosystem II. On further increase in O_3 exposure, it reduces the electron transfer from Photosystem II to Photosystem I (Schreiber et al. 1978).

6.4.3 Effects of Ozone on Respiration and Photorespiration

The respiration in plants is generally found to increase when exposed to ozone above a threshold concentration. The O_3 exposure can either raise (Todd 1958; Barnes 1972) or reduce respiration rate in plants. In a study, researchers observed no immediate effect on respiration after O_3 exposure on *Phaseolus vulgaris*, but after long exposure for about 24 h some adverse effects occurred (Pell and Brennan 1973). Furthermore, at 150 ppb concentration of ozone, decreased level of respiration occurred. Ozone exposure also inhibited respiration in *Nicotiana tabacum* leaf mitochondria (Lee 1967).

In several researches it is observed that the rate of photosynthesis also affects the rate of respiration in plants. If photosynthetic rate is very high, then a small change in the rate of respiration will not alter carbon balance of the plant, while low photosynthetic rate can cause changes in respiration and thus can affect the development of the plant.

6.4.3.1 Photorespiration

The photorespiratory pathway arises through the oxygenation of ribulose-1,5 bisphosphate (RuBP) by Rubisco that produced one molecule of 3-phosphoglycerate and one molecule of the 2-carbon compound phosphoglycolate. The photorespiratory cycle permits the process of changing of this compound into 3-phosphoglycolate through a number of reactions that controls across three different compartments—chloroplasts, peroxisomes and mitochondria and releases CO_2 and NH_3 (Mouillon et al. 1999). Lots of studies show that photorespiration adversely affected leaf phenology in ozone-treated leaves during photosynthesis process (Bagarda et al. 2008).

Stromal CO_2 concentration reduced when low stomatal conductance will promote photorespiration, thus reducing the C:O ratio. In the light one of the factors activating stomatal closure, dry period and salt/osmotic stress are noted. Despite that, many bacterial pathogens that capture on the leaf through the stomata, such as *P syringae*, can also activate this response (Melotto et al. 2008).

6.5 Conclusion and Future Recommendations

The present review concludes that several morphological parameters do get affected by the air pollutant-induced stress. Stress caused by air pollution results in decreased photosynthetic rate, chlorophyll content, stomatal conductance, net photosynthetic carbon dioxide assimilation and carboxylation effectiveness. These parameters primarily include leaf characteristics like cuticle, stomata, etc. The leaf stats in turn influence gaseous exchanges including respiration and photorespiration in plants which further increase environmental stress. It is imperative to understand that effect of individual pollutants is quite different from each other and also from species to species. For instance, NO_x in low concentration acts as a growth promoter.

Environmental stress along with the plant response towards them leads to an eventual slow-down of total biomass growth rate. The need of the hour is to address the knowledge gap in quantification of effect of individual pollutants as well as in combined form on stress physiology. Even the changes observed are small, yet they play a critical role in existence of plant in stress. It should remain in mind that the overall effects of air pollutants on physiological parameters are not exclusive of each other. All of them are inter dependent and the remedial actions should include the holistic measures to balance the ecosystem stability and socio-economic upgradation.

References

Abeyratne VDK, Ileperuma OA (2006) Impact of ambient air pollutants on the stomatal aperture of Argyreiapopulifolia. Ceylon J Sci 35(1):9–15

Aggarwal P (2000) The effect of auto-exhaust pollution on leaf surface of *Cassia siamea* (L.), a road side tree. Acta Ecol 22:101–106

Agrawal M, Verma M (1997) Amelioration of sulphur dioxide phytotoxicity in wheat cultivars by modifying NPK nutrients. J Environ Manag 49(2):231–244

Aminifar J, Ramroudi M (2014) Ecophysiological aspects of envir-onmental pollutions on growth of plants. Appl Sci Rep 8:99–102

Avron M (1960) Photophosphorylation by swiss-chard chloroplasts. Biochim Biophys Acta 40:257–272

Baek SG, Woo SY (2010) Physiological and biochemical responses of two tree species in urban areas to different air pollution levels. Photosynthetica 48:23–29

Bagard M, Le Thiec D, Delacote E, Hasenfratz-Sauder MP, Banvoy J, Gérard J, Dizengremel P, Jolivet Y (2008) Ozone-induced changes in photosynthesis and photorespiration of hybrid poplar in relation to the developmental stage of the leaves. Physiol Plant 134:559–574

Bagarda M, Le Thiecb D, Delacotea E, Saudera MPH, Banvoya J, Gérard J, Dizengremela P, Jolivet Y (2008) Ozone-induced changes in photosynthesis and photorespiration of hybrid poplar in relation to the developmental stage of the leaves. Physiol Plant 134:559–574

Baldoni E, Genga A, Cominelli E (2015) Plant MYB transcription factors: their role in drought response mechanisms. Int J Mol Sci 16:15811–15851

Barnes RL (1972) Effects of chronic exposure to ozone on photosynthesis and respiration of pines. Environ Pollut 3:133–138

Bengtson C, Grennfelt P, Bostrom C-A, Troeng E, Skarby L, Sjodin A, Peterson K (1982) Deposition and uptake of nitrogen oxides in Scots Pine needles (Pinus sylvestris L.). Report lVL-B 647. Institute for Water and Air Pollution Research, Gothenburg, Sweden

Bergmann E, Bender J, Weigel HJ (1999) Ozone threshold doses and exposure-response relationships for the development of ozone injury symptoms in wild plant species. New Phytol 144 (3):423–435

Bermejo-Orduna R, McBride JR, Shiraishi K, Elustondo D, Lasheras E, Santamaría JM (2014) Biomonitoring of traffic-related nitrogen pollution using Lethariavulpina (L.) Hue in the Sierra Nevada, California. Sci. Total Environ 490:205–212

Betzelberger AM, Yendrek CR, Sun J, Leisner CP, Nelson RL, Ort DR, Ainsworth EA (2012) Ozone exposure response for U.S. soybean cultivars: linear reductions in photosynthetic potential, biomass, and yield. Plant Physiol 160:1827–1839

Biggs AR, Davis DD (1980) Stomatal response of three birch species exposed to varying doses of SO_2. J Am Soc Hortic Sci 100:514–516

Black VJ (1984) The effect of air pollutants on apparent respiration. In: Koziol MJ, Whatley FR (eds) Gaseous air pollutants and plant metabolism. Butterworths, London, pp 231–248

Black CR, Black VJ (1979) The effects of low concentrations ofsulphur dioxide on stomata1 conductance and epidermal cell survi-val in field bean (Viciafiba L.). J Exp Bot 30:291–298

Black VJ, Unsworth MH (1979) Resistance analysis of sulfur dioxide fluxes to Viciafaba. Nature 282:68–69

Breuninger C, Meixner FX, Kesselmeier J (2013) Field investigations of nitrogen dioxide (NO2) exchange between plants and the atmosphere. Atmos Chem Phys 13:773–790

Burkhard J, Eiden R (1994) Thin water films on coniferous needles. Atmos Environ 28:2001–2017

Bytnerowicz A, Omasa K, Paoletti E (2007) Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environ Pollut 147:438–445

Capron TM, Mansfield TA (1976) Inhibition of net photosynthesis in tomato in air polluted with NO and NO_2. J Exp Bot 27:1181–1186

Carlson RW (1983) Interaction between SO_2 and NO_2 and their effects on photosynthetic properties of soybean *Glycine max*. Environ Pollut Ecol Biol 32:11–38

Chaparro-Suarez IG, Thielmann A, Meixner FX, Kesselmeier J (2006) Re-investigation of the nitrogen dioxide (NO_2) uptake by tree species. Geophys Res Abstr 8:706–716

Chaparro-Suarez IG, Meixner FX, Kesselmeier J (2011) Nitrogen dioxide (NO_2) uptake by vegetation controlled by atmospheric concentrations and plant stomatal aperture. Atmos Environ 45:5742–5750

Choi D, Toda H, Kim Y (2014a) Effect of sulfur dioxide (SO_2) on growth and physiological activity in Alnussieboldiana at Miyakejima Island in Japan. Ecol Res 29:103–110

Choi D, Toda H, Kim Y (2014b) Effect of sulfur dioxide (SO_2) on growth and physiological activity in Alnussieboldiana at Miyakejima Island in Japan. Ecol Res 29:103–110

Chung YC, Chung PL, Liao SW (2011) Carbon fixation efficiency of plants influenced by sulfur dioxide. Environ Monit Assess 173:701–707

Coulson CL, Robert L (1974) Heath, Inhibition of the photosynthetic capacity of isolated chloroplasts by ozone. Plant Physiol 53:32–38

Crittenden PD, Read DJ (1978) The effects of air pollution on plant growth with special reference to sulphur dioxide. New Phytol 80(1):49–62

Darrall NM (1989) The effect of air pollutants on physiological processes in plants. Plant Cell Environ 12:1–30

De Kok LJ, Westerman S, Stuiver CEE, Weidner W, Stulen I, Grill D (2002) Interaction between atmospheric hydrogen sulphide deposition and pedosphericsulphate nutrition in *Brassica oleracea* L. Phyton 42:35–44

DeKok LJ (1990) Sulphur metabolism in plants exposed to atmospheric sulphur. In: Rennenberg H, Brunold CH, de vacuoles Kok LJ, Stulen I (eds) Sulphur nutrition and sulphur assimilation in higher plants agricultural aspects. SPB Academic, The Hague, pp 111–130

Dhir B (2016) Air pollutants and photosynthetic efficiency of plants. In: Kulshrestha U, Saxena P (eds) Plant responses to air pollution. Springer, Singapore

Dineva S (2006) Development of leaf blades of *Acer platanoides* in industrially contaminated environment. Dendrobiology 55:25–32

Dizengremel P (2001) Effects of ozone on the carbon metabolism of forest trees. Plant Physiol Biochem 39:729–742

Eller ASD, McGuire KL, Sparks JP (2011) Responses of sugar maple and hemlock seedlings to elevated carbon dioxide under altered above- and belowground nitrogen sources. Tree Physiol 31:391–401

Erisman JW, Bleeker A, Galloway J, Sutton MS (2007) Reduced nitrogen in ecology and the environment. Environ Pollut 150:140–149

Farage PK, Long SP (1999) The effects of O3 fumigation during leaf development on photosynthesis of wheat and pea: an in vivo analysis. Photosynth Res 59:1–7

Farage PK, Long SP, Lechner EG, Baker NR (1991) The sequence of change within the photosynthetic apparatus of wheat following short-term exposure to ozone. Plant Physiol 95:529–535

Fatima N, Akram M, Shahid M, Abbas G, Hussain M, Nafees M, Wasaya A, Tahir M, Amjad M (2018) Germination, growth and ions uptake of moringa (*Moringa oleifera* L.) grown under saline condition. J Plant Nutr 41(12):1555–1565

Freer-Smith PH (1985) The influence of SO_2 and NO_2 on the growth, development and gas exchange of *Betula pendula* Roth. New Phytol 99:417–430

Gebler A, Rienks M, Rennenberg H (2000) NH_3 and NO_2 fluxes between beech trees and the atmosphere—correlation with climatic and physiological parameters. New Phytol 147:539–560

Gheorghe IF, Ion B (2011) The Effects of air pollutants on vegetation and the role of vegetation in reducing atmospheric pollution. In: The impact of air pollution on health, economy, environment and agricultural sources. Intech Publisher, Shanghai, pp 256–259

Grennfelt P, Bengtson C, Skarby L (1983) Dry deposition of nitrogen dioxide to Scots pine needles. In: Pruppacher HR, Semonin RG, WGN S (eds) Precipitation scavenging, dry deposition, and resuspension. Volume 2. Dry deposition and resuspension proceedings of the fourth international conference, November–December 1982, Santa Monica, CA. Elsevier, New York, NY, pp 753–762

Guderian R (2012) Air pollution: phytotoxicity of acidic gases and its significance in air pollution control, vol 92. Springer, Berlin

Hetherington AM, Woodward FI (2003) The role of stomata in sensing and driving environmental change. Nature 424:901–908

Hill AC, Bennett JH (1970) Inhibition of apparent photosynthesis by nitrogen oxides. Atmos Environ 4:341–348

Horii CV, Munger JW, Wofsy SC, Zahniser M, Nelson D, McManus JB (2004) Fluxes of nitrogen oxides over a temperate deciduous forest. J Geophys Res 109:D08305

Horsman DC, Wellburn AR (1975) Synergistic effect of SO_2 and NO_2 polluted air upon enzyme activity in pea seedlings. Environ Pollut 8:122–133

Hu KD, Tang J, Zhao DL, Hu LY, Li YH, Liu YS, Jones R, Zhang H (2014) Stomatal closure in sweet potato leaves induced by sulfur dioxide involves H_2S and NO signaling pathways. Biol Plant 58:676–680

Hu YB, Bellaloui N, Tigabu M, Wang JH, Diao J, Wang K, Yang R, Sun GY (2015) Gaseous NO_2 effects on stomatal behavior, photosynthesis and respiration of hybrid poplar leaves. Acta Physiol Plant 37:39

Hultengren S, Gralen H, Pleijel H (2004) Recovery of the epiphytic lichen flora following air quality improvement in south-west Sweden. Water Air Soil Pollut 154:203–211

Jacobson MZ, Seinfeld JH, Carmichael GR, Streets DG (2004) The effect on photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel vehicles. Geophys Res Lett 31: L02116. https://doi.org/10.1029/2003GL018448

Jaradat MR, Feurtado JA, Huang D, Lu Y, Cutler AJ (2013) Multiple roles of the transcription factor AtMYBR1/AtMYB44 in ABA signaling, stress responses, and leaf senescence. BMC Plant Biol 13:192

Julia P, Kangasjärvi VJ (2015) Plant signalling in acute ozone exposure. Plant Cell Environ 38:240–252

Jung C, Seo JS, Han SW, Koo YJ, Kim CH, Song SI, Nahm BH, Choi YD, Cheong JJ (2008) Overexpression of AtMYB44 enhances stomatal closure to confer abiotic stress tolerance in transgenic Arabidopsis. Plant Physiol 146:623–635

Kaur S (2004) Stomatal responses of lemon (*Citrus medica*) to exhaust emissions from vehicles using different types of fuel. Pollut Res 23:451–454

Khan MR, Khan MW (1993) The interaction of SO_2 and root-knot nematode on tomato. Environ Pollut 81:91–102

Knabe W (1976) Effects of sulfur dioxide on terrestrial vegetation. J Hum Environ 5:213–218

Knudson LL, Tibbitts TW, Edwards GE (1977) Measurement of ozone injury by determination of leaf chlorophyll concentration. Plant Physiol 60:606–608

Koziol MJ, Whatley FR (2016) Gaseous air pollutants and plant metabolism. Butterworth-Heinemann, Oxford

Kulshrestha U, Saxena P (eds) (2016) Plant responses to air pollution. Springer

Kumari S, Prakash I (2015) Changes in micromorphology of plant Sidaveronicaefolia in response to air pollution stress in Meerut city. Proceeding of the UGC Sponsored National Seminar on “The Role of Biology in Bringing Second Green Revolution”, India

Lane PI, Bell JNB (1984a) The effects of simulated urban air pollution on grass yield: Part 1 – Description and simulation of ambient pollution. Environ Pollut Ser B 8:245–263

Lane PI, Bell JNB (1984b) The effects of simulated urban air pollution on grass yield: Part 2 – Performance of Loliumperenne, Phleumpratense and Dactylisglomerate fumigated with SO_2, NO_2 and/or NO. Environ Pollut Ser A 35:97–12

Lee TT (1967) Inhibition of oxidative phosphorylation and respiration by ozone in tobacco mitochondria. Plant Physiol 42:691–696

Leffler HR, Cherry JH (1974) Destruction of enzymatic activities of corn and soybean leaves exposed to ozone. Can J Bot 52(6):1233–1238

Lichtenthaler HK, Buschmann C, Knapp M (2005) How to correctly determine the different chlorophyll fluorescence parameters and the chlorophyll decrease ratio RFd of leaves with the PAM fluorometer. Photosynthetica 43:379–393

Liu Y, Li Y, Li L, Zhu Y, Liu J, Li G, Lin H (2017) Attenuation of sulfur dioxide damage to wheat seedlings by coexposure to nitric oxide. Bull Environ Contam Toxicol 99:146–151

Majernik O, Mansfield TA (1971) Direct effect of SO_2 pollution on the degree of opening of stomata. Nature 227:377

Mansfield TA, Freer-Smith PH (1981) Effects of urban air pollution on plant growth. Biol Rev 56:343–368

Marais EA, Jacob DJ, Choi S, Joiner J, Belmonte-Rivas M, Cohen RC, Ryerson TB, Weinheimer AJ, Volz-Thomas A (2017) Nitrogen oxides in the global upper troposphere interpreted with cloud-sliced NO_2 from the Ozone Monitoring Instrument. EGU Gen Assem 19:121–156

Martn A, Barber FR (1984) Acid gases and acid in rain monitored for over 5 years in rural east-central England. Atmos Environ 18:1715–1724

Mazarura U (2012) Effect of sequences of ozone and nitrogen dioxide on plant dry matter and stomatal diffusive resistance in radish. Afr Crop Sci J 20:371–384

Melotto M, Underwood W, He SY (2008) Role of stomata in plant innate immunity and foliar bacterial diseases. Annu Rev Phytopathol 46:101–122

Middleton JT, Darley EF, Brewer RF (1958) Damage to vegetation from polluted atmospheres. J Air Pollut Control Assoc 1958(8):9–15

Miller A, Tsai CH, Hemphill D, Endres M, Rodermel S, Spalding M (1997) Elevated CO_2 effects during leaf ontogeny. Plant Physiol 115:1195–1200

Moldau H, Sober J, Sober A (1993) Impact of acute ozone exposure on CO2 uptake by two cultivars of *Phaseolus vulgaris* L. Photosynthetica 28:133–141

Mouillon JM, Aubert S, Bourguignon J, Gout E, Douce R, Rebeille F (1999) Glycine and serine catabolism in nonphotosynthetic higher plant cells: their roll in C1 metabolism. Plant J 20 (2):197–205

Mudd JB (1975) Sulfur dioxide. In: Responses of plants to air pollution. Academic Press, New York

Mukherjee A, Agrawal M (2018) Use of GLM approach to assess the responses of tropical trees to urban air pollution in relation to leaf functional traits and tree characteristics. Ecotoxicol Environ Saf 152:42–54

Munzi S, Pisani T, Loppi S (2009) The integrity of lichen cell membrane as a suitable parameter for monitoring biological effects of acute nitrogen pollution. Ecotoxicol Environ Saf 72:2009–2012

Nash TH (1976) Sensivity of lichenes of NO_2 fumigation. Bryologist 79:103–106

Okano K, Totsuka T (1986) Absorption of nitrogen dioxide by sunflower plants grown at various levels of nitrate. New Phytol 102:551–562

Olszyk DM, Tibbitts TW (1981) Stomatal response and leaf injury of Pisumsativum L. with SO_2 and O_3 exposures I. Influence of pollutant level and leaf maturity. Plant Physiol 67:539–544

Omasa K, Saji H, Youssefian S, Kondo N (2002) Air pollution and plant biotechnology—prospects for phytomonitoring and phytoremediation. In: De Kok LJ, Stuiver CEE, Westerman S, Stulen I (eds) Elevated levels of hydrogen sulphide in the plant environment: nutrient or toxin. Springer, Tokyo, pp 201–219

Pal A, Kulshreshtha K, Ahmad KJ, Yunus M (2000) Changes in leaf surface structures of two avenue tree species caused by auto exhaust pollution. J Environ Biol 21:15–21

Paoletti E, Grulke NE (2005) Does living in elevated CO2 ameliorate tree response to ozone? A review on stomatal responses. Environ Pollut 137(3):483–493

Park JS, Shin JW, Ahn TT, Son JE (2010) Analysis of CO_2 and harmful gases caused by using burn-type CO_2 generators in greenhouses. J Bio-Environ Control 19:177–183

Pell EJ, Brennan E (1973) Changes in respiration, photosynthesis, adenosine 5′-triphosphate, and total adenylate content of ozonated Pinto Bean foliage as they relate to symptom expression. Plant Physiol 51:378–381

Pell EJ, Eckardt N, Enyedi AJ (1992) Timing of ozone stress and resulting status of ribulose bisphosphatase carboxylase/oxygenase and associated net photosynthesis. New Phytol 120:397–405

Pell EJ, Eckardt NA, Glick RE (1994) Biochemical and molecular basis for impairment of photosynthetic potential. Photosynth Res 39:453–462

Rahmat M, Maulina W, Rustami E, Azis M, Budiarti DR, Seminar KB, Yuwono AS, Alatas H (2013) Performance in real condition of photonic crystal sensor based NO_2 gas monitoring system. Atmos Environ 79:480–485

Rai A, Kulshreshtha K (2006) Effect of particulates generated from automobile emission on some common plants. J Food Agric Environ 4:253–259

Ranieri A, Castagna A, Gian BB, Soldatini F (2001) Iron deficiency differently affects peroxidase isoforms in sunflower. J Exp Bot 52(354):25–35

Rao IM, Amundson RG, Alscher-Herman R, Anderson LE (1983) Effects of SO_2 on stomatal metabolism in Pisumsativum L. Plant Physiol 72:573–577

Raschk K (1975) Stomatal action. Annu Rev Plant Physiol 26:309–340

Reich PB, Amundson RG (1985) Ambient levels of ozone reduce net photosynthesis in tree and crop species. Science 230(4725):566–570

Reinert RA, Shriner DS, Rawlings JO (1982) Responses of radish to all combinations of three concentrations of nitrogen dioxide, sulfur dioxide, and ozone. J Environ Qual 11:52–57

Rey A, Jarvis PG (1998) Long-term photosynthetic acclimation to increased atmospheric CO_2 concentration in young birch (*Betula pendula*) trees. Tree Physiol 18:441–450

Robinson MF, Heath J, Mansfield TA (1998) Disturbances in stomatal behaviour caused by air pollutants. J Exp Bot 49:461–469

Rogers HH, Jeffries HE, Witherspoon AM (1979) Measuring air pollutions uptake by plants: nitrogen dioxide. J Environ Qual 18:551e557

Sabaratnam S, Gupta G (1988) Effects of nitrogen dioxide on biochemical and physiological characteristics of soybean. Environ Pollut 55:149–158

Saxe H, Murali NS (1989) Diagnostic parameters for selecting against novel spruce (*Picea abies*) decline: 11. Response of photosynthesis and transpiration to acute NO_2 exposures. Physiol Plant 76:349–355

Saxena P, Kulshrestha U (2016a) Biochemical effects of air pollutants on plants. In: Plant responses to air pollution. Springer, Singapore, pp 59–70

Saxena P, Kulshrestha UC (2016b) The impact of gasoline emission on plants–a review. Chem Ecol 32(4):378–405

Saxena P, Naik V (eds) (2018) Air pollution: sources, impacts and controls. CABI

Saxena P, Sonwani S (2019a) Primary criteria air pollutants: environmental health effects. In: Criteria air pollutants and their impact on environmental health. Springer, Singapore, pp 49–82

Saxena P, Sonwani S (2019b) Criteria air pollutants: chemistry, sources and sinks. In: Criteria air pollutants and their impact on environmental health. Springer, Singapore, pp 7–48

Saxena P, Sonwani S (2019c) Secondary criteria air pollutants: environmental health effects. In: Criteria air pollutants and their impact on environmental health. Springer, Singapore, pp 83–126

Saxena P, Sonwani S (2020) Criteria air pollutants and their impact on environmental health. Springer, Singapore

Saxena P, Sharma Y, Chugh M (2017, December). Assessment of ozone phytotoxic potential of dense vegetation cover of Delhi by AOT40. In AGU fall meeting abstracts

Saxena P, Srivastava A, Tyagi M, Kaur S (2019) Impact of tropospheric ozone on plant metabolism – a review. Pollut Res 38(1):175–180

Schmutz P, Tarjan D, Günthardt-Goerg MS, Matyssek R, Bucher JB (1995) Nitrogen dioxide – a gaseous fertilizer of Poplar trees. Phyton 35:219–232

Schreiber U, Vidaver W, Runeckles VC, Rosen P (1978) Chlorophyll fluorescence assay for ozone injury in intact plants. Plant Physiol 61:80–84

Seyyednejad SM, Koochak H (2011a) Some morphological and biochemical responses due to industrial air pollution in Prosopisjuliflora (Swartz) DC plant. Afr J Agric Res 8(18):1968–1974

Seyyednejad SM, Koochak H (2011b) Some morphological and biochemical responses due to industrial air pollution in *Prosopis juliflora* (Swartz) DC plant. Afr J Agric Res 8 (18):1968–1974

Sobrado MA (2011) Leaf pigment composition and fluorescence signatures of top canopy leaves in species of the upper Rio Negro forests. Res J Bot 6:141–149

Sonwani S, Kulshreshtha U (2016) Particulate matter levels and it's associated health risks in East Delhi. Proceedings of Indian aerosol science and technology association conference on aerosol and climate change: insight and challenges. IASTA Bull 22(1–2). ISSN 09714510

Sonwani S, Maurya V (2018) Impact of air pollution on the environment and economy. In: Air pollution: sources, impacts and controls. CABI Publisher, Oxford. ISBN 9781786393890

Sonwani S, Saxena P (2016) Identifying the sources of primary air pollutants and their impact on environmental health: a review. IJETR 6(2):111–130

Sonwani S, Saxena P, Kulshrestha U (2016) Role of global warming and plant signaling in BVOC emissions. In: Plant responses to air pollution. Springer, Singapore, pp 45–57

Srivastava HS, Jolliffe PA, Runeckles VC (1975) The influence of nitrogen supply during growth on the inhibition of gas exchange and visible damage to leaves by NO_2. Environ Pollut 9:35–47

Stulen I, Perez-Soba M, De Kok LJ, Van der Eerden L (1998) Impact of gaseous nitrogen deposition on plant functioning. New Phytol 139:61–70

Takagi M, Gyokusen K (2004) Light and atmospheric pollution affect photosynthesis of street trees in urban environments. Urban For Urban Green 2:167–171

Taylor GE, Johnson DW, Andersen CP (1994) Air pollution and forest ecosystems: a regional to global perspective. J Ecol Appl 4:662–689

Teklemariam TA, Sparks JP (2006) Leaf fluxes of NO and NO_2 in four herbaceous plant species: The role of ascorbic acid. Atmos Environ 40:2235–2244

Thoene B, Rennenberg H, Weber P (1996) Absorption of atmospheric NO2 by spruce (Piceaabies) trees: II. Parameterization of NO_2 fluxes by controlled dynamic chamber experiments. New Phytol 134:257–266

Todd GW (1958) Effect of ozone and ozonated I -hexene on respiration and photosynthesis of leaves. Plant Physiol 33:416–420

Unsworth MH, Ormrod DP (eds) (1982) Air pollution in agriculture and horticulture. Book chapter – Godzik S, Krupa SV, Effects of sulfur dioxide on growth and productivity of crop plants (pp 247–265). Butterworths, London

Vahisalu T, Puzo I, Brosche M, Valk E, Lepiku M, Moldau H, Pechter P, Wang YS, Lindgren O, Salojarvi J, Loog M, Kangasjarvi J, Kollist H (2010) Ozone-triggered rapid stomatal response involves the production of reactive oxygen species, and is controlled by SLAC1 and OST1. Plant J 62:442–453

Verma A, Singh SN (2006) Biochemical and ultrastructural changes in plant foliage exposed to auto-pollution. Environ Monit Assess 120:585–602

Wellburn AR (1990) Why are atmospheric oxides of nitrogen usually phytotoxic and not alternative fertilizers? New Phytol 115:395–429

Weller R, Jones AE, Wille A, Jacobi HW, McIntyre HP, Sturges WT, Huke M, Wagenbach D (2002) Seasonality of reactive nitrogen oxides (NOy) at Neumayer Station, Antarctica, 107 (D23), ACH 2-1–ACH 2-11

Whitmore ME, Mansfield TA (1983) Effects of long-term exposure to SO_2 and NO $_2$ on Poapratensis and other grasses. Environ Pollut Ser A 31:217–235

Wilkinson S, Mills G, Illidge R, Davies WJ (2012) How is ozone pollution reducing our food supply? J Exp Bot 63:527–536

Xu J, Yin H, Liu X (2010) Nitric oxide is associated with long term zinc tolerance in Solnumnigrum. Plant Physiol 154(3):1319–1334