Chapter 9
Morpho-anatomical, Physiological, Biochemical and Molecular Responses of Plants to Air Pollution

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Contents

1 Introduction

In the recent past, air pollution has become a growing concern. Globally, the number of air pollution incidents is increasing in many cities. The World Health Organization (WHO) has pointed out that climate change is one of the serious health threats of the twenty-first century, and air pollution is considered as the single largest environmental health risk (WHO 2016a). Further, according to a report published by WHO (2016b), indoor and outdoor air pollution is accountable for about seven million deaths every year. It has been estimated that around 800 people per hour, or 13 people per minute, die due to dirty air quality. Almost, four million of these deaths are noticed in the Asia-Pacific region. Commonly associated diseases related to air pollution are stroke and heart disease, respiratory illness and cancers. At the same time, these air pollutants also damage the climatic condition; for instance, fine particles of black carbon from fossil fuel combustion and increase in

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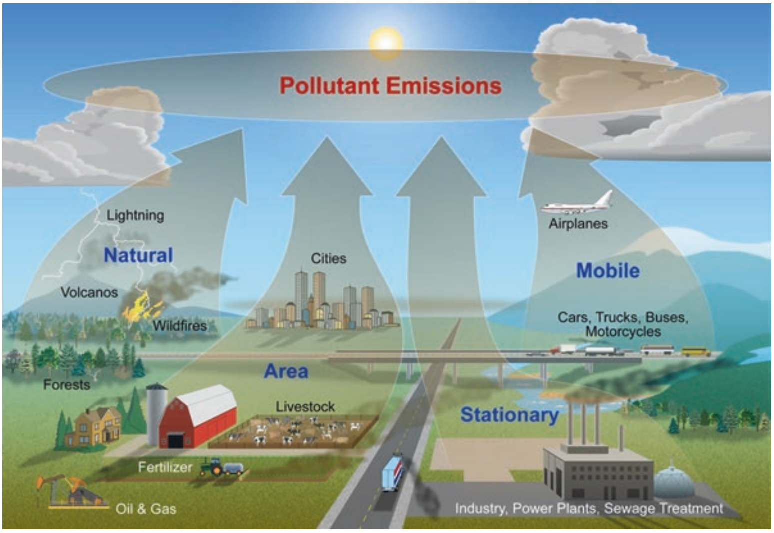

Fig. 9.1 Sources of air pollution. (Adapted from NPA 2018)

the ground level of ozone concentration have shown various adverse impacts at the global level. Several sources of air pollution have been illustrated in Fig. 9.1.

Very recently, in Wuhan (China) due to the outbreak of a new coronavirus (COVID-19), the National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) pollution monitoring satellites have noticed a remarkable decrease in nitrogen dioxide over China. Figure 9.2 represents nitrogen dioxide concentrations, across China from January 1–20, 2020 (before the quarantine) and February 10–25 (during the quarantine). According to NASA, the levels of nitrogen dioxide (a pollutant mainly released by burning fossil fuels) were down as much as 30% (NASA 2020). Similarly, to combat with COVID-19 in India, a 'Janta Curfew' on March 22, and thereafter for 21 days, the world's largest lockdown (with around 130 billion people) imposed from March 24, 2020, to April 14, 2020, resulted in a significant improvement in the air quality of the country as monitored by the Central Pollution Control Board (CPCB). According to the data from CPCB, out of the 103 Indian cities where air quality was recorded, 23 registered 'good' air quality whereas 65 others recorded satisfactory air quality (CPCB 2020). At the same time, new data showing pollution levels over Europe showed a marked decline in pollutants, particularly nitrogen dioxide, over northern Italy (ESA 2020). Thus, certainly, this situation will decrease health-related problems associated with our planet. However, until the genesis of this book chapter, no vaccine has been invented to cure pandemic COVID-19; and the world is facing an unprecedented challenge with communities.

Plants are sessile in nature, and fixed permanently at the site of germination, thus often handle changing and challenging environmental conditions (both abiotic and biotic stresses). Air pollutants (mainly carbon monoxide, lead, nitrogen

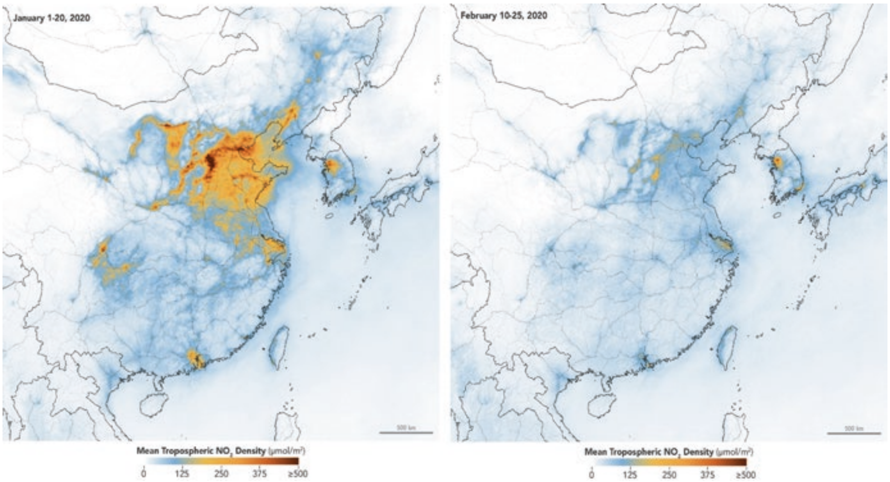

Fig. 9.2 February satellite readings in the troposphere (the lower atmosphere) of nitrogen dioxide, a pollutant primarily released from burning fossil fuels, show a dramatic decline compared to early January when power plants were operating at normal levels. (Adapted from NASA observatory 2020)

oxides, sulphur oxides, ground level of ozone and particulate matters) and/or poor air quality influenced plant health and developed an adverse impact. To escape from such kinds of challenges, plants develop different types of strategies, physical barriers as well as inducible defence mechanisms. Several investigation have been carried out to examine the impact of air pollution on the various aspects of plants such as growth and development, foliar morphology, biochemical changes and various enzymatic activities (Gupta and Ghouse 1987; Husen et al. 1999; Husen and Iqbal 2004; Joshi et al. 2009; Iqbal et al. 2010a, b; Adrees et al. 2016; Yadav et al. 2019; Mukherjee et al. 2019; Ainsworth et al. 2020). Additionally, it has also been noticed that many plant species released some kinds of fine particles such as pollen, spores and other fine particles which have shown to produce allergic response in humans.

Some reports have shown both so-called immediate (acute) and long (chronic) impacts of air pollution on plant growth and developmental processes (Shaibu-Imodagbe 1991; Husen 1997; Jean-Pierre 2020), which may depend on the types of plant species, exposure time, concentration and types of pollutants. Anthropogenic (industrial emission, coal-based power plant emission, vehicular emission, etc.) or naturally produced air pollutants, often transported from one place to another, create haze, get deposited on the various plant species which create changes/harmful impacts on plants' biological activities (Fig. 9.3). Further, their impact may vary according to the source of pollution, types of pollutant, season, wind direction and velocity, exposure duration, plant species and so on.

Coal-based power stations emit many pollutants such as sulphur dioxide, nitrogen oxides, mercury, lead, particulates and various other heavy metals and damage plant growth and production (Husen et al. 1999; Nighat et al. 1999, 2008; Husen

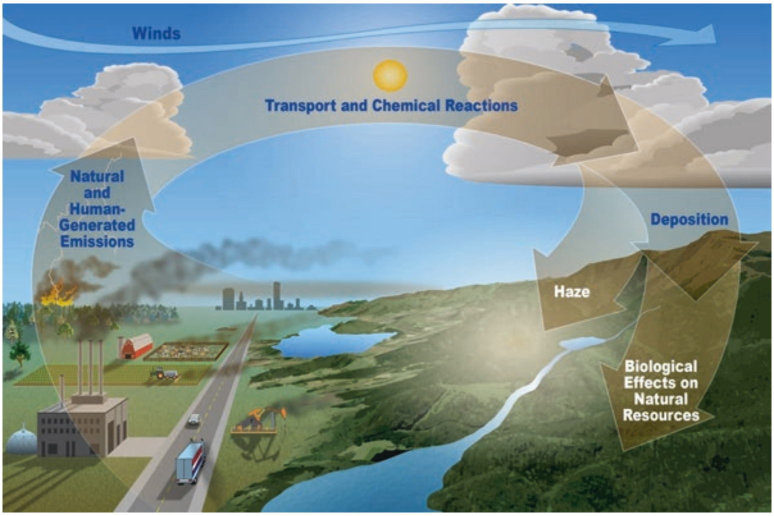

Fig. 9.3 Wind can move air pollutants short or very long distances before they cause harmful impacts. (Adapted from NPA 2018)

and Iqbal 2004; Iqbal et al. 2010a, b; Qadir et al. 2016, 2019). These pollutants have shown visible as well as an invisible injury on vegetation. In this case also, the extent of injury depends on the concentration of gases, fumigation frequency, exposure duration and other prevailing environmental conditions. Additionally, fly ash is another inorganic product obtained by the combustion of organic coal in boilers at power stations. Some reports have shown that fly ash when applied to soil at low doses increased plant growth and decreased at high doses (Pandey and Singh 2010; Shaheen et al. 2014; Yao et al. 2015). However, in terms of positive response, these studies warranted to evaluate the potential risk caused by the presence of heavy metal in fly ash; thus, its feasibility to use in agricultural practices need detailed investigations. Further, it has also been reported that some plant species have been used for remediation and/or mitigation of pollutants from air, soils and water (Nivane et al. 2001; Iqbal et al. 2015; Wei et al. 2017). In this situation, usually plants assimilate, degrade or modify the toxic impact of pollutants to less toxic ones and plants are able to utilize them. Thus, these plant species could be utilized in passive monitoring or mitigation of air pollution in a particular locality.

A number of pollutants (carbon monoxide, nitrogen oxides, sulphur dioxide, ammonia, methane, nonmethane volatile organic compounds, particulate matter and toxic heavy metals) are released by vehicles (Bell et al. 2011). Out of these, toxic metals such as lead, cadmium, manganese, molybdenum, copper, antimony, zinc, arsenic, platinum, palladium and rhodium are the principal pollutants and have been observed as the main contaminants (Wang and Zhang 2018; Khalid et al. 2018). It has also been reported that roadside plantation reduced particulate matter pollution as they are deposited on the leaf surface (Heisler et al. 1995; Steffens et al. 2012; Brantley et al. 2014; Tong et al. 2016; Baldauf 2017; Khalid et al. 2019). In this connection, leaf types, leaf thickness, presence of leaf hair or trichomes, epicuticular wax, etc. are important in terms of pollution load reduction. Baldauf (2017) reported that roadside plantation influenced nearby air quality, both in a positive and negative way. Thus, if appropriately planned, plantation barriers can be used to upgrade on-road or near-road air quality status, either alone or in combination with some kind of solid noise barriers.

In the light of the above-mentioned discussion, the present chapter was undertaken to understand and assess the current advances in the development of plant response to major air pollutants, with special reference to structural, functional, biochemical/metabolic responses, gene expression and yield attributes.

2 Responses of Plants to Air Pollution

Gaseous air pollutants are absorbed by the leaf surface or stomata (Jean-Pierre 2020) (Fig. 9.4). Additionally, these pollutants, in very low concentrations, may also enter through stems and trunk. Depending on the type of leaf surface (leaf structure, thickness, presence of leaf hair or trichomes, epicuticular wax, water

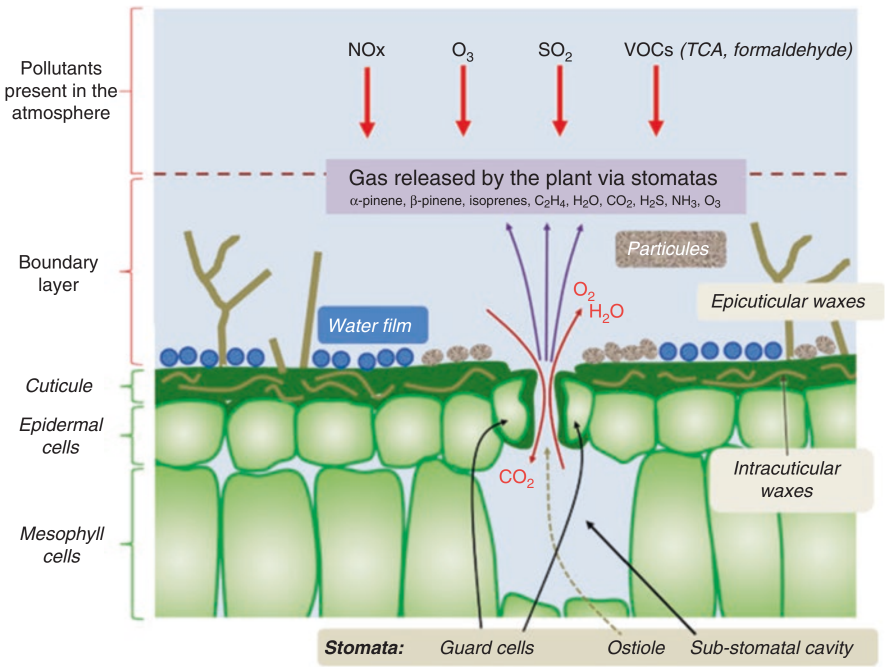

Fig. 9.4 Plant leaf surface and stomata – preferred site of gaseous pollution exchange. (Adapted from Jean-Pierre 2020)

film, etc.), concentration/type of air pollutant, they may penetrate and/or react on the leaf surface.

Occasionally, the reaction of air pollutants on the leaf surface forms acids which are more toxic than the pollutants (Smith 1990; Husen 1997). During these exercises, plants may experience temporary or even permanent damage, for instance chlorosis, bleaching, mottling and necrosis (Husen et al. 1999; Cavanagh and Clemons 2006). For instance, normal (pollution-free site; Jamia Hamdard, New Delhi, India) and polluted (maximum pollution load area of Badarpur Power Plants, New Delhi, India) sites were chosen for comparative investigation. In this experiment, *Datura innoxia* plants grown in polluted area/sites have shown various symptoms on the leaf as presented in Fig. 9.5. Overall, exposure to sulphur dioxide, nitrogen oxides, ozone, particulate matters and some heavy metals have been reported to alter important morpho-physiological (biomass, leaf traits, gas exchange characteristics, etc.), anatomical, biochemical/metabolic and enzymatic activities (Yunus and Iqbal 1996; Husen et al. 1999; Husen and Iqbal 2004). Further, the salient findings have been discussed under the following subheadings.

2.1 Response to Sulphur Dioxide Pollution

Sulphur dioxide is produced by combustion of coal, fuel oil and gasoline (because these fuels contain sulphur), and in the oxidation of naturally occurring sulphur gases, for instance, volcanic eruptions. However, the largest source of sulphur dioxide in the atmosphere is the burning of fossil fuels by coal-based power stations and other industrial amenities.

Sulphur dioxide has been investigated more extensively than the other pollutants. Sulphur dioxide shows acute visible injury to plant leaves at high concentrations (Jacobson and Hill 1970; Husen 1997) and invisible injury, involving physiological and biochemical changes at low concentrations (Husen 1997; Husen et al. 1999; Husen and Iqbal 2004; Nighat et al. 1999, 2008). It has also been noticed that sulphur dioxide is the major air pollutant produced during the combustion of coal (Smith 1990; Iqbal et al. 2000). In fact, plants growing in the vicinity of a coal-based power station are exposed to an array of air pollutants which interact and affect plant morphology and metabolism. For instance, let us compare a case study: in *D. innoxia* (Husen 1997), the number of leaves per plant was slightly reduced but leaf length, single leaf area and total leaf area per plant were significantly reduced in the vicinity of a coal-based power station, compared to those at a normal site. In *D. innoxia* plants, the biomass of leaf, stem and root were increased significantly under the polluted condition (Husen 1997). This increase might be due to the greater availability of minerals and trace elements of fly ash origin, namely, sodium, potassium, calcium, magnesium, boron, sulphate (Elsewi et al. 1981; Wong and Wong 1989), copper, zinc, molybdenum and selenium (Furr et al. 1978) and a negligible amount of carbon and nitrogen (Carlson and Adriano 1993) to the growing plant. Some studies confirm that plant biomass may increase due to the presence of fly ash

Fig. 9.5 *Datura innoxia* leaf from (**a**) normal site (pollution free) and (**b**) polluted sites (maximum pollution load) showing the difference in size, and symptoms like necrosis, chlorosis, curling surface and lesion of burn. (Adapted from Husen 1997)

in the soil (Khan and Khan 1996; Singh et al. 1997). In the upper epidermis of *D. innoxia*, stomatal density, stomatal index and size of stomatal pore increased at the polluted site, showing a significant per cent variation. The epidermal cell density, trichome density and trichome size, however, showed a significant loss, whereas the loss was insignificant for stomatal length (Husen 1997) (Fig. 9.6).

In the lower epidermis of *D. innoxia*, stomatal density, stomatal index and size of stomata as well as stoma increased at the polluted site and showed a significant

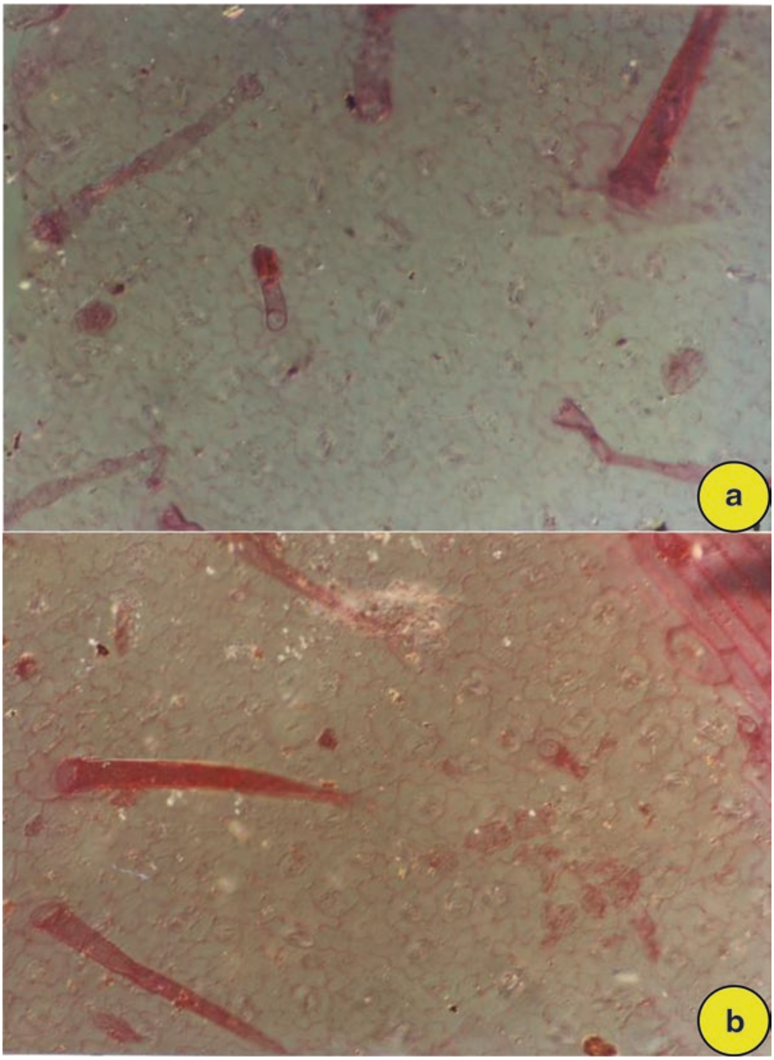

Fig. 9.6 Upper epidermal peel mount from *Datura innoxia* leaf showing the difference in size and shape of epidermal cells as well as size, number and aperture of stomata from normal (pollution free – **a**) and polluted sites (maximum pollution load – **b**). Epidermal cells decreased in the polluted sample, whereas stomata with increased size and aperture were more in number in the polluted sample. (Adapted from Husen 1997)

variation, while epidermal cell abundance, trichome length and trichome density underwent a reduction which was insignificant for the last parameter (Husen 1997) (Fig. 9.7). In rice plants, exposure to sulphur dioxide at concentration have also shown foliar injury at different levels (Agrawal et al. 1982).

Further, in *D. innoxia* plants, the studied metabolic activities (proteins and carbohydrates) also varied, in different plant parts at the normal and polluted sites.

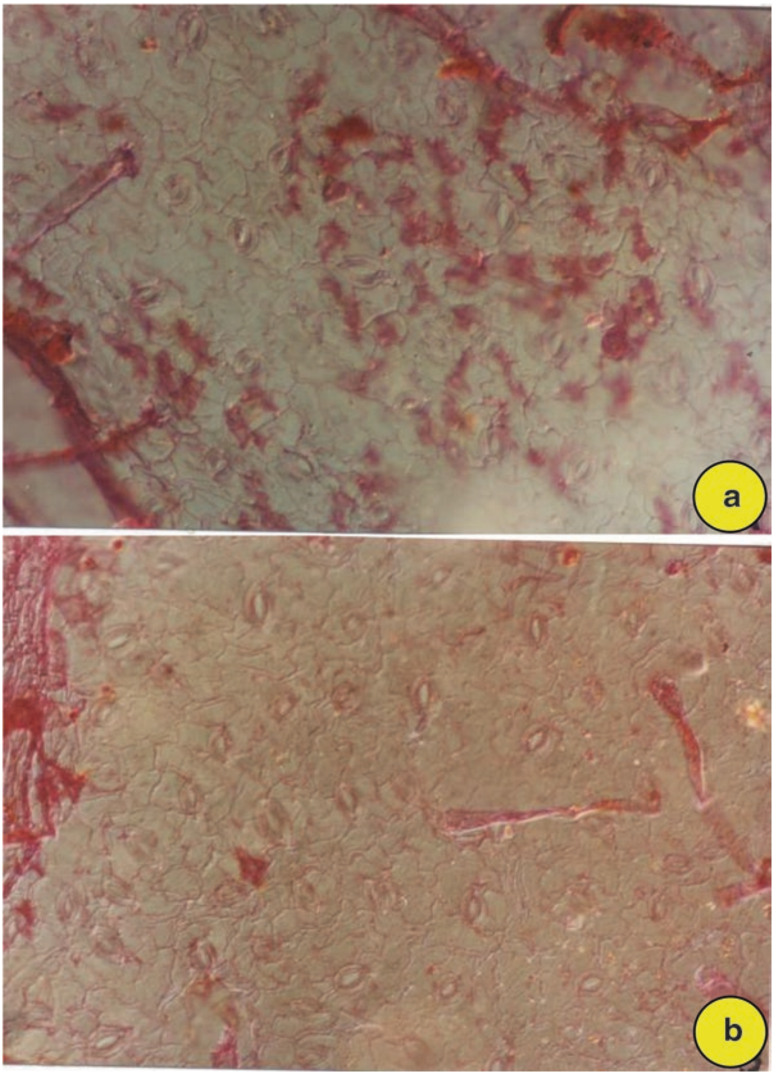

Fig. 9.7 Lower epidermal peel mount from *Datura innoxia* leaf showing the difference in size and shape of epidermal cells as well as the size, number and aperture of stomata from normal (pollution free – **a**) and polluted sites (maximum pollution load – **b**). Epidermal cells decreased in the polluted sample, whereas stomata with increased size and aperture are more in number in the polluted sample. (Adapted from Husen 1997)

Soluble protein in *D. innoxia* leaves at the pollution stress site was noted; this might be due to the toxic effect of sulphur dioxide levels on protein synthesis. This could be due to the decreased rate of photosynthesis, protein synthesis inhibition and/or enhanced protein degradation (Sij and Swanson 1974; Constantinidou and Kozlowski 1979; Husen et al. 1999). A reduction in the content of protein due to exposure to sulphur dioxide has also been detected in many other species. It is known that sulphur dioxide fumigation inactivates enzymes involved in protein synthesis (Nandi et al. 1990; Agrawal and Deepak 2003; Hamid and Jawaid 2009). A reduction in the nitrate reductase activity of *D. innoxia* leaves under pollution stress (Husen 1997) might also be associated with the rate of photosynthesis. Protein, amino acids and certain enzyme activities in leaves, buds and shoots show qualitative as well as quantitative variation with drought, salinity and pollution stress conditions (Parui et al. 2001; Rezanejad 2009; Husen 2010; Getnet et al. 2015; Embiale et al. 2016; Husen et al. 2014, 2017, 2018, 2019; Hussein et al. 2017; Sheng and Zhu 2019). In *D. innoxia*, reducing sugar increased in roots but significantly declined in leave and stem at the polluted site might be due to fly ash deposition in soil (Husen 1997).

Stomatal conductance in the leaves of *D. innoxia* was significantly reduced at the polluted site, confirming some earlier findings (Field et al. 1995; Kull et al. 1996; Kellomäki and Wang 1997; Nighat et al. 2000) which could be because of the reduced rate of photosynthesis (Farage et al. 1991). The photosynthetic rate was significantly suppressed (63.92%) at the polluted site (Husen 1997). Chloroplast disruption could be the reason for the decrease in the net photosynthesis at low concentrations of sulphur dioxide such as 0.035 ppm (Black and Unsworth 1979). Sulphur dioxide may directly affect the process of photosynthesis because its various intercellular derivatives and photo-induced oxidizing free radicals interfere with the metabolic pathway (Malhotra and Khan 1984). Inhibitory effects of sulphur dioxide and oxides of nitrogen pollutants on photosynthesis and carbon dioxide exchanges of plants are well documented. Dust in stomata may prevent stomatal closure which tends to increase the uptake of gaseous air pollutants and water loss (Fluckiger et al. 1979). Both the intensity and direction of stomatal response to carbon dioxide may change due to environmental influence (Morison and Gifford 1983; Mansfield and Atkinson 1990). The intercellular carbon dioxide concentration was raised under pollution stress. In *D. innoxia* plants, the amount of chlorophyll a, b, total chlorophyll and carotenoids decreased significantly under pollution stress conditions (Husen 1997). Chlorophyll loss due to sulphur dioxide pollution has been reported for other species too. Chlorophyll damaged by sulphur dioxide is mainly observed either by its conversion to pheophytin (Rao and LeBlanc 1966) or production of superoxide radicals by the reaction of sulphite with chlorophyll under illumination (Shimazaki et al. 1980). In *D. innoxia* plants, damage to chlorophyll 'a' was relatively greater than that to chlorophyll 'b' in the polluted atmosphere, thus showing a greater degree of sensitivity for the former. However, both the chlorophylls may be equally susceptible in some other species (Singh et al. 1990a). Total chlorophyll and carotenoid contents decreased in tomato leaves with increasing sodium metabisulphate ($Na_2S_2O_3$) concentrations (Singh et al. 1990b). However, carotenoids were more sensitive than chlorophyll to the pollution hazards (Kondo et al. 1980; Khan and Usmani 1988). Sulphur content in *D. innoxia* leaves, stem, roots and seeds of the pollution-affected plants showed a highly significant increase, about 224%, 61%, 54% and 272%, respectively (Husen 1997). Accumulation of sulphur in plant tissues has been used as an indicator of sulphur dioxide stress in air pollution studies. Pollen viability of *D. innoxia* plants was significantly decreased under pollution stress thus indicating a negative effect on the reproductive capacity of the stressed plants (Husen 1997). Reduced pollen viability due to air pollution has also been reported earlier (Ostrolucka 1989; Bellani and Paoletti 1992).

Comparative data on stem anatomy of *D. innoxia* plant growing at the normal and polluted sites were examined (Husen 1997) (Figs. 9.8 and 9.9). There was a significant increase in the width of vessel elements and fibres in the stem at the polluted site, the gain being to the tune of 11% and 23%, respectively. The length of both the cell types registered a decrease which was quite significant in the case of fibres. The number of vessels per unit transverse area also decreased, though it was insignificant. Stem diameter in the second internode from the ground was greater at the polluted site. The area occupied by the cortex and vasculature was also greater. However, the area of the pith was considerably reduced showing nearly 24% loss. Additionally, the comparative root anatomy of *D. innoxia* plant growing at the normal and polluted sites were also investigated (Husen 1997) (Figs. 9.10 and 9.11). The overall size of fibres and vessel elements in the root

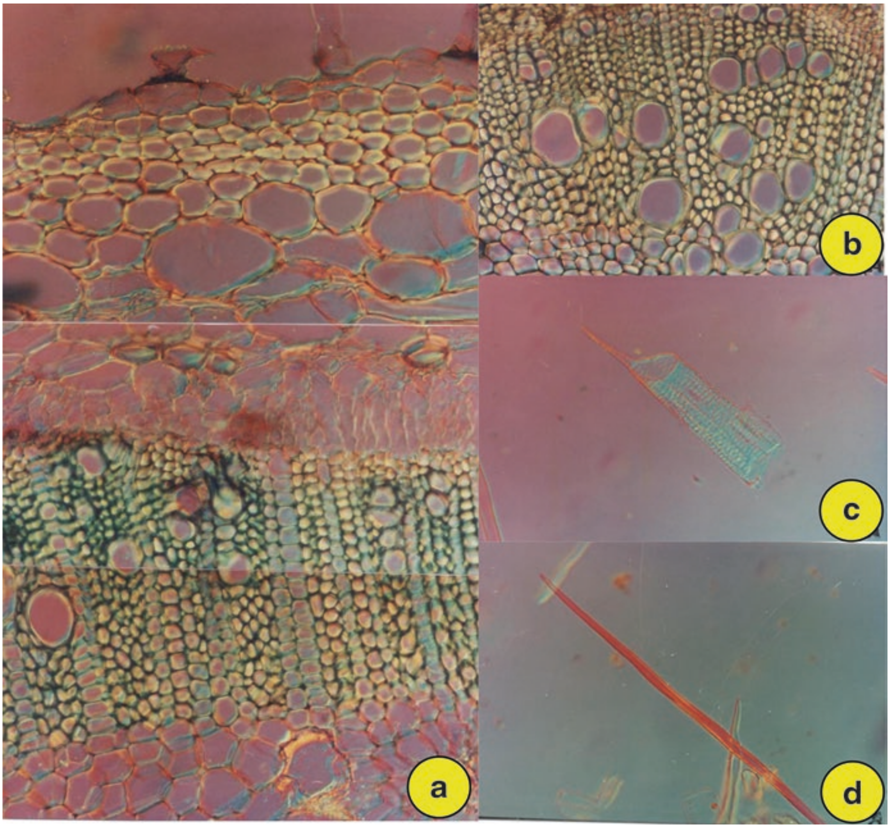

Fig. 9.8 Transverse section of normal stem of *Datura innoxia* (**a**) number and size of vessel (**b**, **c**) and fibre (**d**). (Adapted from Husen 1997)

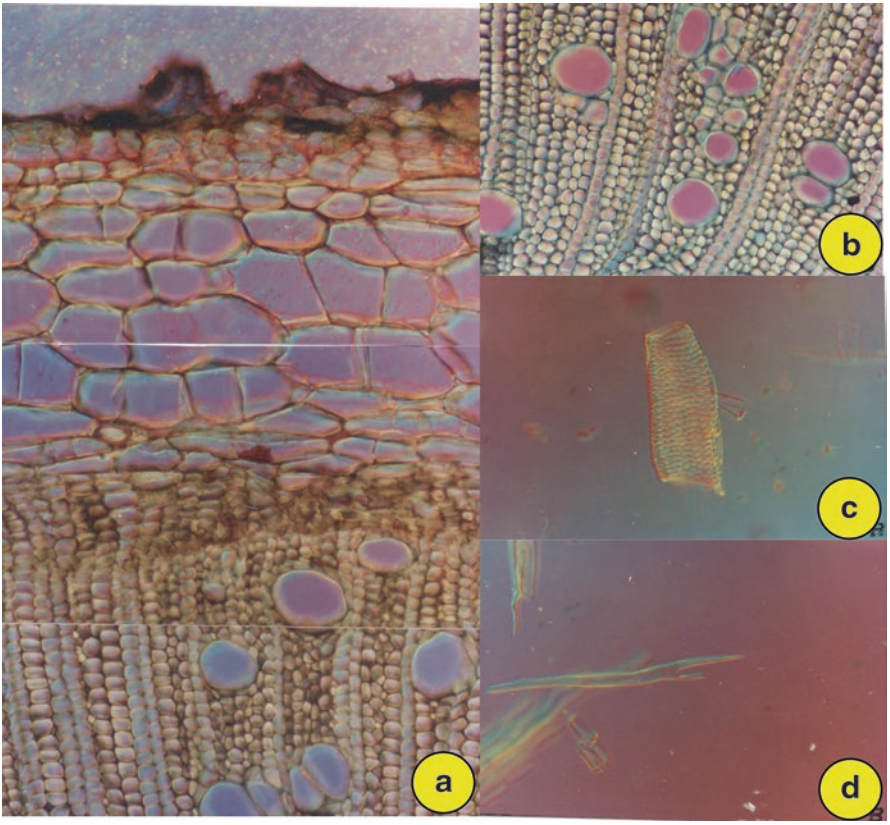

Fig. 9.9 Transverse section of polluted stem of *Datura innoxia* (**a**) number and size of vessel (**b**, **c**) and fibre (**d**). (Adapted from Husen 1997)

increased insignificantly at the polluted site. The total number of vessels per unit transverse area exhibited an insignificant increase in the stressed samples. Root diameter was significantly greater, showing about 30% gain. The area of the cortex was greatly reduced by about 57%, while areas of vasculature and pith increased more. Further, an insignificant reduction, showing only 6% variation, was observed in the vulnerability ratio (VR) of the stressed plant, hence their degree of xeromorphy correspondingly increased. Taken together, the size of the xylem cells such as fibres and vessel elements may increase or decrease due to coal-based pollution. Such studies have also been carried out both in the root and stem (Ghouse et al. 1985, 1986; Iqbal et al. 1986, 1987a, b; Iqbal et al. 2010a, b). Further specific reason for these bidirectional variations has yet to be identified (Pozgaj et al. 1996). In *D. innoxia*, vessel frequency declined in the polluted stem and increased in the polluted root. Of the areas of the cortex, vasculature and pith, the first was significantly reduced in the root, whereas the last did so in the stem at the polluted site. A slight decrease in stem axis circumference and in the proportion of cortex and xylem was reported earlier in *Cajanus cajan* (Ghouse et al.

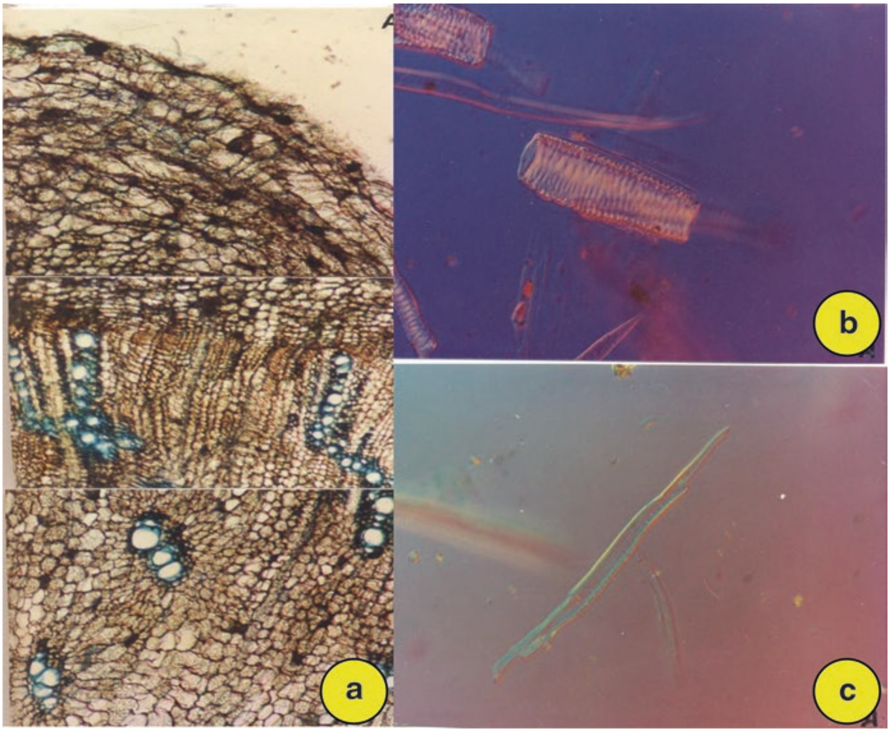

Fig. 9.10 Transverse section of normal root of *Datura innoxia* (**a**) size of vessel (**b**) and fibre (**c**). (Adapted from Husen 1997)

1989). Pollutants may reduce xylem increment even when visible leaf symptoms are absent (Thompson 1981). Decreased xylem increment in mature trees could be established by growth sign analysis (Thompson 1981; Pozgaj et al. 1996). Likewise, a decrease in stem pith of *Xanthium strumarium* under coal-smoke pollution was observed (Ansari et al. 1993). In many cases, roots of the polluted plant show better growth though stem growth declines. This could be due to deposition and uptake of fly ash that has all mineral nutrients, except nitrogen, required for the normal growth of a plant. Ariel plant parts possibly remain away from drawing benefit from this situation because of the impact of air pollutants to which they are sensitive. Air pollution influences not only the amount but also the structure of wood (Pozgaj et al. 1996). The mesophyll as well as the VR of wood, an indicator of ecological adaptation of woody plants, decreased in *D. innoxia* under stress, thus showing a tendency of the plants towards becoming more xeromorphic in characters. Overall, several investigations have been carried out by different researchers to examine the impact of sulphur dioxide and in general other air pollutants on the plant growth and survival, foliar morphology, stem and root anatomy, and biochemical changes and various physiological aspects at contaminated sites. And, the extent of injury to plants depends on the concentration of gases, fumigation frequency, exposure duration and other prevailing environ-

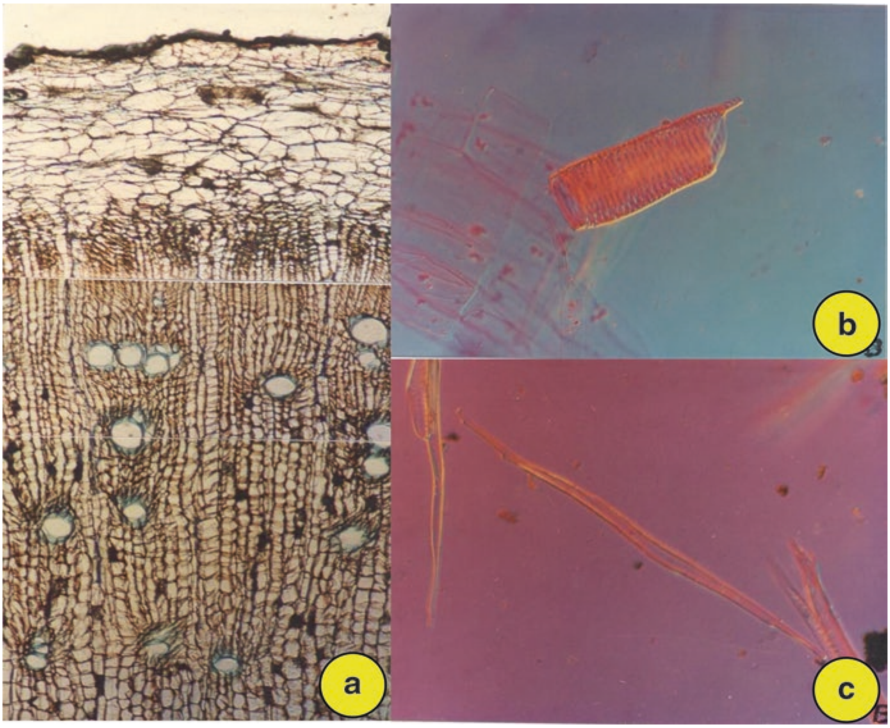

Fig. 9.11 Transverse section of polluted root of *Datura innoxia* (**a**) size of vessel (**b**) and fibre (**c**). (Adapted from Husen 1997)

mental conditions (Yunus and Iqbal 1996; Husen 1997; Husen and Iqbal 2004; Iqbal et al. 2010b; Khalid et al. 2019).

2.2 Response to Nitrogen Oxide Pollution

Nitrogen oxide and other oxides of nitrogen react with other chemicals in the air and produce nitrogen dioxide. The major anthropogenic sources are the combustion of fossil fuels such as coal, gas and oil. Additionally, it is produced from nitric acid preparation, welding and using explosives, refining of petrol and metals, commercial manufacturing and food manufacturing. However, natural sources are volcanoes and bacteria. Globally, its emission has been increasing (NASA observatory 2020) due to the higher industrial production and other associated automobile activities. It is also a precursor of secondary air pollutants, that is, ozone and particulate matter (Rahmat et al. 2013; Bermejo-Orduna et al. 2014; Marais et al. 2017). Nitrogen oxide may reach the plant system either directly through its foliar deposition or indirectly through rainwater or soil deposition. It enters the leaf, either through open stomata or the cuticles; of these, the access through the stomata is dominant. Its entry is governed by various factors like plant species, types of leaf, exposure duration and concentration. Researchers have two opinions about the plant response to nitrogen oxide. The first opinion is that, by being metabolized and incorporated in the nitrate assimilation pathway, nitrogen dioxide is able to form organic nitrogenous compounds and not harm plant leaves (Middleton et al. 1958; Stulen et al. 1998). Further, the second opinion is that many plants show both low amounts of NO_2-N incorporation into total plant nitrogen and resistance to NO_2 (Nakaji et al. 2001). In an investigation, Mansfield et al. (1982) reported that at very high levels (up to 3500 ppb) of NO_X (mainly NO) in glasshouses have reduced plant growth. Takahashi et al. (2005, 2014) and Takahashi and Morikawa (2014) recognized atmospheric NO and NO_2 as either detrimental or beneficial for plant development. Exposure to nitrogen oxide triggered physiological responses such as antioxidant enzyme activities, N metabolic activity and components/distribution of nitrogenous metabolic products in various plant tissues (Norby et al. 1989; Teklemariam and Sparks 2006; Liu et al. 2015; Vighi et al. 2017). Further, it has been reported that at a lower dose (0.1 μl L^{-1} NO_2) insignificantly affected 1-year-old *Buxus sinica* seedlings' height, leaf area and dry weight (Dochinger and Jensen 1985) and at 0.5 μl L^{-1} NO_2 significantly stimulated the leaf growth of Carolina poplar (*Populus canadensis* Moensch 'Eugenei') and Lombardy poplar (*Populus nigra* L. 'Italica'); nonetheless, a higher dose (1 μl L^{-1} NO_2) significantly decreased stem growth (Eastham and Ormrod 1986). In a recent study, Sheng and Zhu (2019) suggested that NO_2 causes a pollution risk to plant, but the antioxidant activities play a significant role in the protection of plant against NO_2-induced oxidative damage.

2.3 Response to Ozone Pollution

The surface level of ozone (three atoms of oxygen) is formed by the reaction of gaseous pollutants in the presence of sunlight. Further, its photochemical productions are influenced by variations in solar irradiation, temperature and precursor amount and relative proportion (such as methane, carbon monoxide, volatile organic compounds and nitrogen oxide compounds). Accordingly, its surface concentration may vary from one place to another, and can be transported over long distances by wind. Thus, they may affect even productivity of plants in rural areas and on agricultural lands. Additionally, the natural ozone layer is found in the lower portion of the stratosphere (15–35 km) above the earth surface. Usually, its thickness varies geographically, and from one season to another (NOAA 2008). This is a protective ozone layer and does an important job. It absorbs the radiation (ultraviolet light) from the sun, preventing it from reaching the earth surface. Gradual thinning or depletion of the stratosphere ozone layer due to the reaction of ozone and chlorofluorocarbon gases is a major environmental problem since it increases the ultraviolet radiation that reaches the earth surface. These radiations are linked to many injurious effects in humans, animals, plants and natural ecosystem. However, technically, ozone in the troposphere is considered as a greenhouse gas which may also contribute to climate change (NASA 2018).

Plant response to elevated ozone has been investigated by many researchers (Fuhrer et al. 2016; Jolivet et al. 2016; Li et al. 2017; Yendrek et al. 2017; Mills et al. 2018; Shang et al. 2019; Peng et al. 2019; Ghosh et al. 2020). Ozone-induced damages in plants occur with stomatal entrance, lead to the production of ROS causing oxidative stress, and finally, influence the process of photosynthesis, plant growth and accumulation of biomass in various plant species (Ainsworth et al. 2012; Hassan et al. 2017). In an experiment, Rai and Agrawal (2012) showed that ozone negatively influenced the rate of photosynthesis by affecting photosynthetic pigments, chlorophyll fluorescence (Fv/Fm) and electron transport along with carbon fixation in terms of reduced Rubisco activity and quantity. It was also noticed that the photosynthate translocation and allocation also get affected due to ozone, which influenced crop yield and reproduction features such as modulation of pollen or ovule maturation, changes in the timing, rate or number of flowers produced, effects on seed and fruit development, yields, seed germinability and seedling vigour. Very recently, Ghosh et al. (2020) used two sowing dates (timely sown and late sown) to examine the impact of elevated ozone on *Triticum aestivum* cv. HD 2967 growth including biomass, leaf gas exchange rate and other yield features (i.e. the length of the ear plant^{-1}, weight of ears plant^{-1}, number of grains plant^{-1}, weight of grains plant^{-1}, husk weight plant^{-1}, straw weight plant^{-1}, harvest index, test weight of the grains and straw grain ratio). In this study, they concluded that ozone exposure affected growth and productivity; and late sowing practice is not advisable for wheat cultivation. Various studies have shown that exposure to ozone affected negatively the rate of photosynthesis and other associated physiological activities in wheat (Feng et al. 2008; Ghosh et al. 2020), soybean (Morgan et al. 2003), rice (Ainsworth 2008), radish and brinjal (Tiwari and Agrawal 2011). Reduced rate of assimilation was ascribed to decreased carboxylation efficiency, and was associated with reduced Rubisco activity (Leitao et al. 2007). Sarkar and Agrawal (2010) suggested that the degree of ozone-induced foliar injury depends on the duration and concentration of its exposure. Reduced rate of photosynthesis may also be noticed due to damage of thylakoids, which influenced photosynthetic transport of electron and is shown by a decrease in the Fv/Fm ratio. Quite often, the Fv/Fm ratio is associated with plant stress condition evaluation (Husen 2010). A decreased Fv/Fm ratio represents changes in PS II photochemistry and are related to photoinhibition. A reduction in the Fv/Fm ratio in the leaves of lettuce (Calatayud et al. 2002), rice (Ishii et al. 2004), wheat (Francini et al. 2007) and snap bean (Flowers et al. 2007) under ozone exposure has been reported. As observed by different investigators, exposure to ozone affected plant biomass, carbon assimilation, translocation and accumulation in various plant parts which can be associated with the reduced rate of photosynthesis (Grantz and Farrar 2000; Morgan et al. 2003; Fuhrer and Booker 2003; Biswas et al. 2008). In rice plants, Agrawal et al. (2002) reported a reduction in the level of RNA transcript for the small subunit of Rubisco, photosynthetic gene expression under ozone stress. Further, Sarkar and Agrawal (2010) also noticed reduced levels of mRNA (both small and large subunits of Rubisco) in the same plant under ozone stress.

2.4 Response to Carbon Dioxide Pollution

Atmospheric concentrations of carbon dioxide have also been increasing quickly due to global industrial revolution (Canadell et al. 2007). Further, it has been reported that the global concentration of carbon dioxide will increase continuously in future due to various anthropogenic activities (Yunus and Iqbal 1996). It is colourless, odourless, non-flammable gas at room temperature. However, it can be a liquid or a solid at other temperatures and pressure. Its exposure to humans causes various effects such as headaches, dizziness, restlessness, breathing problem, sweating, tiredness, increased heart rate, elevated blood pressure, coma, asphyxia, etc. Plant growth and production response to elevated carbon dioxide have shown both positive and negative impacts. In terms of positive impacts, elevated carbon dioxide accelerated photosynthesis and subsequently higher growth, biomass and plant yield (Ainsworth and Long 2005; De Souza et al. 2008; van der Kooi et al. 2016). However, in terms of negative impacts, elevated carbon dioxide has shown a reduced variety of nutrients including protein concentrations, vitamins and some macro- and micro-elements in plants (Myers et al. 2014; Fernando et al. 2015; Broberg et al. 2017; Thompson et al. 2019). Hence, it is necessary to understand the overall impact of elevated carbon dioxide on plant growth and production.

The elevated level of atmospheric carbon dioxide significantly influenced photosynthesis, metabolism and development of plant (Nowak et al. 2004; Ainsworth and Long 2005). Some researchers presumed that C_4 photosynthesis was saturated at ambient carbon dioxide and that C_4 plants might be less and/or not at all affected by the accelerated level of carbon dioxide in comparison to C_3 plant species (Pearcy and Ehleringer 1984; Bowes 1993). Perhaps, this assumption appeared on the anatomical and functional variation of C_3 and C_4 plant species and higher carbon dioxide levels in bundle sheath cells of C_4 leaves. But many investigations have shown that the variation between C_3 and C_4 is not as important as anticipated, and that C4 plants can also increase remarkably the rates of photosynthesis under elevated carbon dioxide conditions. For instance, Ziska and Bunce (1997) examined and found an increase in growth by 3–25% and stimulation of photosynthesis by 4–30% in six weedy species (*Amaranthus retroflexus*, *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Setaria faberi*, *Setaria viridis* and *Sorghum halapense*) and 4 crop species (*Amaranthus hypochondriacus*, *Saccharum officinarum*, *Sorghum bicolor* and *Zea mays*) under elevated carbon dioxide conditions. De Souza et al. (2008) reported that elevated carbon dioxide levels enhance the rate of photosynthesis, biomass and productivity, and modify gene expression in sugarcane (C_4

plant). More specifically, plants grown at elevated carbon dioxide conditions (~720 ppm) showed the rate of photosynthesis enhanced by 30%, height by 17% and biomass by 40% in comparison to plants grown under ambient carbon dioxide (~370 ppm) conditions. They also showed stomatal conductance to be lowered by −37%, transpiration rates by −32% and water-use efficiency to be increased by 62%. Further, under elevated carbon dioxide conditions, cDNA microarray studies have shown a differential expression of 35 genes on the leaves (14 repressed and 22 induced). The latter is mostly associated with the photosynthetic processes and development. However, in maize (C_4 plant) and sorghum (C_4 plant), an increase in plant productivity was not noticed in terms of grain yield and kernel number under elevated carbon dioxide and well-watered conditions (Ottman et al. 2001; Leakey et al. 2006).

Yilmaz et al. (2017) studied the role of potassium deficiency on plant growth as affected by elevated carbon dioxide; and how antioxidant defence systems respond to potassium deficiency under ambient (400 ppm) or elevated (900 ppm) atmospheric carbon dioxide conditions in durum (*Triticum durum* cv. Sarıçanak-98) and bread wheat (*Triticum aestivum* cv. Adana-99). They found that low or deficient supply of potassium induced oxidative stress, but elevated carbon dioxide had an insignificant impact on antioxidant defence systems and therefore could not alleviate the detrimental impacts of potassium deficiency. In this study, the responses in antioxidant defence enzymes were linked to the potassium nutritional status of plants rather than elevated carbon dioxide conditions. Recently, Thompson et al. (2019) studied 19 wheat genotype (five tetraploid, 11 hexaploid and three synthetic hexaploid) grain protein concentration under elevated carbon dioxide conditions. They examined whether decreased protein grain is genotype dependent and whether it is caused by biomass dilution. In most of the genotypes, the total grain protein was increased, while most genotypes exhibited decreased grain protein concentration under elevated carbon dioxide conditions. In this study, elevated carbon dioxide revealed an increase in grain biomass for all genotypes and total shoot biomass for most genotypes, with the harvest index increasing for all genotypes except for the two synthetic hexaploids CPI133814 and CPI133811. They found that most of the differences between wheat types were insignificant; and suggested that the individual genotype of wheat plants determines the response to elevated carbon dioxide rather than the wheat type.

Elevated carbon dioxide has also enhanced soil-labile C input and, therefore, more microbial carbon source, thus increasing gene abundances in N cycling, such as *nifH*, *amoA*, *nirS* and *nirK* (He et al. 2010, 2014). However, the impact of elevated carbon dioxide on plant N uptake and microorganisms is changeable due to other environmental factors (Butterly et al. 2016). Very recently, Dong et al. (2020) studied the impact of three (ambient, elevated and super-elevated) levels of carbon dioxide concentrations and two N application rates (low and high) on N uptake of cucumber plants and N cycling in a greenhouse soil in open-top chambers. In this study, elevated carbon dioxide enhanced biomass by 24% and N concentration by 4% of fine roots due to high N application, suggesting an improvement in N uptake efficiency. The improvement was greater under low N application but to a lesser extent under super-elevated carbon dioxide conditions. Further, elevated carbon dioxide and super-elevated carbon dioxide exhibited a decrease in gene abundances of soil bacterial *amoA*, *nirS* and *nosZ* in high N applications with increased plant N uptake and reduced NH_4^+, NO_2^- and NO_3^- concentrations in soils resulting in less soil N loss. They suggested that a moderate carbon dioxide enrichment increases N uptake efficiency in the fine roots of cucumber plants and decreases soil N loss associated with decreased nitrification and denitrification under high N applications. Palacios et al. (2019) assessed plant development, seed yield and composition under elevated carbon dioxide and high temperature. A network of relationships among biochemical parameters of grains at three developmental stages revealed that ambient carbon dioxide and high temperatures, as well as elevated carbon dioxide and high temperatures, *affected* significantly both carbohydrate and lipid metabolisms. Additionally, the comparison of ambient carbon dioxide/ambient temperature and elevated carbon dioxide/high temperatures showed insignificant variation in the studied parameters. Abo Gamar et al. (2019) reported that elevated carbon dioxide reduces the negative effects of high temperature and drought conditions by mitigating oxidative stress and improving water status in *Arabidopsis thaliana.* Balasooriya et al. (2020) reported that elevated carbon dioxide (950 ppm) and higher temperature (30 °C) increased the amounts of accessible bioactive compounds in strawberries. Interestingly, in a very recent experiment, Nedunchezhiyan et al. (2020) suggested that rice seed priming with salicylic acid (25 mg l^{-1}) and ascorbic acid (100 mg l^{-1}) increased germination, other seed quality parameters, α-amylase activity and antioxidant enzyme activities under stress due to elevated carbon dioxide and temperatures.

Further, it has also been reported that the elevated carbon dioxide is likely to cause changes in plant diseases (Lake and Wade 2009), tolerance to insect herbivory by pests (Lau and Tiffin 2009), changes in defence signalling (Zavala et al. 2008) and plant-to-plant interaction/competitiveness (Brooker 2006). Thus, these relationships may also lead to certain changes in ecosystems and help look for an interdisciplinary approach to manage and implement adaptive approaches specially to ensure plant production, growth, food and overall security of the ecosystem in near future.

2.5 Response to Particulate Matter Pollution

Due to rapid industrialization and other anthropogenic processes (automobiles, power plants, construction sites, unpaved roads, fields, smokestacks or fires, etc.) various types of particulate matters (also known as particle pollution) are emitted into the atmosphere. Some amounts of natural origin of dust or particulate matters have also been noticed. They are solid particles and/or liquid droplets. Some of the particles, for instance dust, dirt, soot, smoke, are visible to the naked eye. However, others are very small and can only be observed under an electron microscope. These particles can be inhaled, cause serious health problems and are well documented (Brook et al. 2003; Mcdonald et al. 2007; Thomas and Richard 2010; Ulrich et al. 2012). Vegetation in the vicinity (or in the urban area) of such kinds of pollutants (such as cement, coal-dust, fly ash, automobile exhaust and other airborne particulates) has shown remarkable impacts on morphological, biochemical, physiological and genetic status (Farooq et al. 2000; Rai et al. 2010; Younis et al. 2013; Rai et al. 2016; Yu et al. 2018, Karmakar and Padhy 2019). The deposited solid particles may alter the optical properties of leaves; due to this adverse effect, a decrease in chlorophyll content and an increase in the production of antioxidant activities are often observed. These processes finally lead to leaf senescence. Additionally, it has also been reported that some plant species improve urban air quality (Freer-Smith et al. 1997) due to the presence of specific types of foliar features such as leaf orientation, contact area, roughness, epidermal cell arrangement, types, frequency and length of trichomes and so on. Meusel et al. (1999) suggested that the foliage of plants filter many solid particles and thus can be helpful in decreasing the negative impact of particulate pollution. Sharma et al. (2005) also examined the ability of *Bougainvillea* sp. to intercept dust and its use in bio-aesthetic planning and roadside plantation as dust filters. Prusty et al. (2005) have reported that the dust interception capacity in plants depends on their canopy shape and size, leaf phyllotaxy and leaf surface features such as hairs and cuticle. In roadside plant species, the dust interception capacity has also shown seasonal variation (Prajapati and Tripathi 2008). Further, it has also been noticed that the structure and composition of epicuticular wax particles may also contribute towards the dust-capturing capacity of plants (Dzierzanowski et al. 2011). In a very recent experiment, Peng et al. (2020a, b) reported that the enclosed space had a lower particulate matter concentration than the outdoor environment; plants are able to reduce indoor particulate matter concentrations because they increased the surface area of the space. Overall, some plant species exhibited tolerance mechanisms and/or substantial degree of damage under particle pollution load leading to inhibition of photosynthetic activities, protein synthesis and so on. In this state of affairs, some plants became prone to damage caused by insects, nematodes and microbes. At the same time, some kinds of adaptation have also been noticed at the physiological, biochemical and genotoxic levels.

2.6 Response to Fluoride Pollution

Fluoride compounds are considered as another main problem due to its hazardous impact on ecosystems (ATSDR 2003; Divan Jr et al. 2008). They are released into the atmosphere in gaseous state (hydrogen fluoride and silicon tetrafluoride) as well as in solid particles. It enters the atmosphere from anthropogenic sources in large quantities by aluminium smelters, fertilizer factories, coal-burning operation and industrial activities, namely tile, pottery and cement works, ceramic, glass manufacture industries and so on (Cape et al. 2003). However, naturally at the global level, volcanic eruptions, rock dust and/or marine environment contribute very less amounts of fluoride compounds emission into the atmosphere (Barnard and Nordstrom 1982; Saether et al. 1995). In recent years, even though the fluoride emitters have been equipped with effective filters, its emission into the atmosphere continues and leads to various problems (Franzaring et al. 2006). Airborne fluoride deposition and distribution depend on several factors, like level of emission, particulate grain size, chemical reactivity and different meteorological conditions (Hara et al. 1998; Scheringer 2009; Yanchenko and Baranov 2010; Gasic et al. 2010; Walna et al. 2013). Adverse impacts of fluoride pollution in humans, plants and the entire ecosystems are well documented (ATSDR 2003; Feng et al. 2003; Divan Jr et al. 2008; Jha et al. 2011; Sharma and Kaur 2018). In the plant system, fluoride penetrates through absorption by stomata or cuticle, thus leaf is the most affected plant organ. Feng et al. (2003) reported that fluoride enters into the plant system and influences its metabolic activities. Many researchers have reported the associations between atmospheric fluoride and accumulation of fluoride in plant leaves and between fluoride in soil solution and fluoride taken up by different plant species (Klumpp et al. 1996; Karolewski et al. 2000; Fangmeier et al. 2002; Doley 2010; Koblar et al. 2011).

Cai et al. (2016) reported that higher doses of fluoride ($\geq$5 mg L^{-1}) decreased the rate of photosynthesis and chlorophyll fluorescence in tea (*Camellia sinensis*) leaves. However, plant leaf has produced more epidermal hairs to reduce water loss under stress conditions. Elloumi et al. (2017) conducted an experiment on *Eriobotrya japonica* to investigate the impact of fluoride air pollution from a phosphate fertilizer factory. They found that fluoride stress negatively influenced foliar water status, photosynthetic parameters, cell membranes and photosynthetic pigments. Exposure to potassium fluoride for a period of 27 days in simulated rain was found to be extremely toxic to *Eugenia dysenterica* plants (Rodrigues et al. 2017). In this study, cell viability as indicated by anatomical leaf alterations (necrosis on the adaxial side, from the border to the centre and tissue degradation with the formation of cellular plasmolysis and elongation) and alterations in chlorophyll a fluorescence parameters was adversely affected under fluoride exposure. Further, Rodrigues et al. (2017) reported the presence of phenolic compounds and accumulation of starch in leaves exposed to potassium fluoride stress; this suggests the response of the plant to the oxidative stress caused. Oliveira dos Anjos et al. (2018) examined the response of *Spondias purpurea* to potassium fluoride using simulated fog (15 mg L^{-1} for 20 min daily up to 10 days). Plants have shown fluoride accumulation, marginal and apical necrosis, presence of phenolic compounds, anatomical alterations and leaflet abscission in young leaves. Similarly, Sharma and Kaur (2019) examined fluoride-mediated antioxidant defence responses in *Spirodela polyrhiza*, grown under hydroponic conditions. Plants were exposed to various doses of fluoride (0, 5, 10, 15, 20, 25, 50 ppm) for 24, 72, 120 and 168 h. In this experiment, accumulation of fluoride was noticed at different exposure periods which triggered the oxidative stress as observed from increased electrolyte leakage, proline, anthocyanin and phenolic content. Additionally, *S. polyrhiza* under fluoride stress responded by alterations in antioxidative enzyme activities, which reflects the tolerance ability of plants. Overall, plant response to fluoride compounds has shown a reduction in plant growth, metabolic performances and photosynthetic activity. Further, its impact on plants might be severe, acute or chronic and fluoride phytotoxicity depends on concentration, exposure duration and plant genotype.

3 Conclusion

In the modern society, air pollution is a major global concern due to rapid economic growth accompanied by increased energy consumption. Thus, its injurious link to humans, animals, plants, microbes and natural ecosystems cannot be ignored. It has been noticed that air pollutants, namely sulphur dioxide, nitrogen oxides, ozone, carbon dioxide, particulates, fluoride and various others damage plant growth and production. Their impact on plant system might be acute or chronic and depends on the concentration of pollutants, exposure duration, season and plant genotype. Tree, herb and shrubs differ in terms of physical and chemical nature, and morphology and anatomy of the leaves; thus, accordingly, they are able to escape and/or tolerate when challenged by unfriendly environmental conditions. These pollutants have several harmful effects as they affect plant growth, physiological activities, biochemical attributes, antioxidant activity and gene expression. Exposure to pollutants has shown to modulate photosynthetic pigments, the process of photosynthesis, stomatal functioning, carbon allocation, respiration, protein synthesis, nutrient contents, etc. and increase the production of reactive oxygen species which is very harmful to the metabolic activities of the plants. These changes affect the overall plant system and also disturb microbial flora and fauna associated with the plant. Thus, an integration of important molecular and physiological investigations, combined with agronomic and ecological research, is important to gain better understandings in terms of plant response to air pollution.

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