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Phytomonitoring of Air Pollutants for Environmental Quality Management

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1. Introduction

Presently rapid changes in the Earth system are an issue of prime importance for the sustainability of the biosphere. The physical and chemical features of the Earth are intimately tied to the organisms and the activities required for their sustenance. Anthropogenic disturbances, such as growing population and its consequent increasing needs, rapid industrialization, increased energy consumption and exploitation of the natural resources, have led to a number of negative effects, appearing in the form of pollution and general degradation of the ecology and environment. The biosphere and human organism can cope to a certain extent with these adverse changes, but the level of pollutants and accompanying phenomena, that nature and man can endure without damage, is often exceeded today in a number of developed and developing countries. The pollution has attained such unacceptable levels that vast forest areas have been damaged, agricultural production lowered, and the health of the whole population endangered.

One of the major environmental concerns of today is the excessive pollution of air. Air is a resource not confined by political or geographical boundaries. The human body requires ~50lb of air a day for its oxygen needs (Perkins 1974). If one assumes an average daily consumption of food ~1.5 kg per person, the intake of air is ~15 to 20 times the amount of food. This explains why air quality, which is characterized by the nature of pollutants and their concentrations, is a serious public health and environmental problem.

The pollutants in the atmospheric air may be in solid, liquid and gaseous form e.g., wind blown dust, volcanic dust and gases, sea-spray, oxides of nitrogen and sulfur, hydrocarbons, hydrogen sulfide from decaying organic matters etc. They are transported to the terrestrial and marine surfaces from their sources of origin by wind and turbulence. The mean wind speed in the atmospheric boundary layer varies typically in the range ~5-10 m/sec among regions, thus the horizontal transport of pollutants over a day is typically ~500-1000 km. During transport process, these pollutants may undergo change of form, such as secondary gaseous pollutants and aerosols through chemical reactions under a set of different meteorological conditions in the atmosphere. The transformation of physical and chemical form greatly influences rates of removal of the pollutants from the atmosphere by direct deposition as gases or aerosols to the terrestrial surfaces or marine layers, known as *dry deposition* and by precipitation as *wet deposition*. Atmospheric pollutants may also interact with short-wave and long-wave terrestrial radiation through scattering and absorption processes and thus may cause perturbations in the radiation energy balance of the earth atmospheric system. This may lead to climatic changes which may have local, regional and global repercussions in terms of temperature, rainfall, soil moisture and food production. Excellent reviews of many historical aspects and sources of pollutants, atmospheric transport and transformations of pollutants, and issues of global change are provided in the book by Bell and Treshow (2002). It is, thus, clear that atmospheric pollution has serious consequences not only for human health, but the planet life itself.

In order to mitigate environmental pollutants and to protect the biosphere from the adverse effects of pollution, four important issues should be highlighted explicitly. These issues include changing lifestyle to control or decrease the emissions of pollutants, developing technologies to avoid or mitigate emissions, making rules and regulations to reduce or cut emissions and decontamination of existing pollutants in the environment. Gaseous pollutants and particulates, once released in the atmosphere, disperse rapidly. Mechanical treatment processes in such situation are very energy-intensive and costly; while plants are driven by solar energy, self-reproducing and concentrate and detoxify pollutants. The ability of a plant to clean up dispersed ambient pollutants has been confirmed in a number of studies (Hill 1971; Okano et al. 1988; Simonich and Hites 1994, 1995; Weber et al. 1995; Yunus et al. 1996; Salt et al. 1998; Pacala et al. 2001). Thus, plant is a natural monitor and detoxifier “device” of toxic pollutants in our ambient environment while adding value to our buildings, landscapes, and communities.

Air pollution has both direct and indirect impacts on plant life. It has been known for several decades that air pollution can adversely affect plant health. Many studies have been conducted on the responses of plants to air pollution (Treshow 1984; Posthumus 1985; Hutchinson and Meema 1987; Heck et al. 1988; Treshow and Anderson 1991; Alscher and Wellburn 1994; Alfani et al. 1996; DeKok and Stulen 1998). Studies have also demonstrated a relationship between trace gas emissions and agricultural crops with respect to CH_4 and N_2O in particular (Singh 2000). Amongst these, a number of studies were carried out under controlled exposure conditions inside the chamber. The results from chamber studies are valuable and can provide casual links between pollution and onset of injuries to plants; nevertheless field survey reveals the integrated effects of pollutants on the plants over longer duration under different pollutant mixtures and set of environmental conditions (Lee et al. 2004).

Plant injury symptoms by air pollutants are most common near large cities, smelters, refineries, electric power plants, airports, highways, refuse dumps, pulp and paper mills, and coal-, gas- or petroleum-burning furnaces. Damage to plants and vegetations in isolated areas also occurs when pollutants are spread long distances by the wind under different climatic conditions. Damage to vast forested areas in Europe and North America is a good example of long-range transport of pollution (Bell and Treshow 2002). Injuries to plants due to air pollution include mottled foliage, “burning” at leaf tips or margins, twig dieback, stunted growth, premature leaf drop, delayed maturity, abortion or early drop of blossoms, and reduced yield or quality. In general, the visible injuries to plants are of three types: (1) collapse of leaf tissue with the development of necrotic patterns, (2) yellowing or other color changes, and (3) alterations in growth or premature loss of foliage.

The transport of gaseous pollutants and aerosols from the atmosphere to vegetation is by the turbulent wind field, generated by the frictional drag by the vegetation surfaces on the wind. It is this turbulent wind field that drives exchange of scalar concentrations between vegetation and the atmosphere. The aerodynamically rough surfaces like, forests and vegetation, generate much greater frictional drag on airflow than flat terrain and as a consequence, the rates of transport of pollutants from free atmosphere to the surface are much greater over forests and vegetation than over short vegetation or flat terrain. Thus, the nature of surface strongly affects the rate of transfer. This turbulent transfer of pollutants to the vegetation surface, together with processes at the surface, determines the uptake of gases and capture of aerosols by plants (Fig. 1).

Plants are very sensitive to the surrounding habitats. Alteration in normal environmental conditions, such as temperature, wind, light, soil water content, nutrients and air pollutants, directly affects the physiology of plant functioning like, developing injuries, abnormal symptoms or growth. Injury is often evident on plants before it can affect human being and other animals. The appearance of such abnormal symptoms/injuries or growth is a good indicator of the danger of environmental pollution to human beings. Some plants are relatively tolerant to air pollutants, and so can accumulate pollutants. The possible use of plants as passive monitors/indicators was early recognized (Bleasedale 1973; Harward and Treshow 1975; Roose et al. 1982). Phillips (1980) outlined the criteria for suitable bioindicator species that include relative tolerance to pollution exposure; abundant presence; sedentary habit; ease of laboratory holding and testing; and the ability to accumulate some pollutants and hence show dose-response relationship. Canas et al. (1997) further categorized the plants, used for biomonitoring of air pollutants into two: (1) sensitive species in which visible injuries indicate damage, and (2) tolerant species that can accumulate pollutants and demonstrate dose-response relationships. In a more recent study,

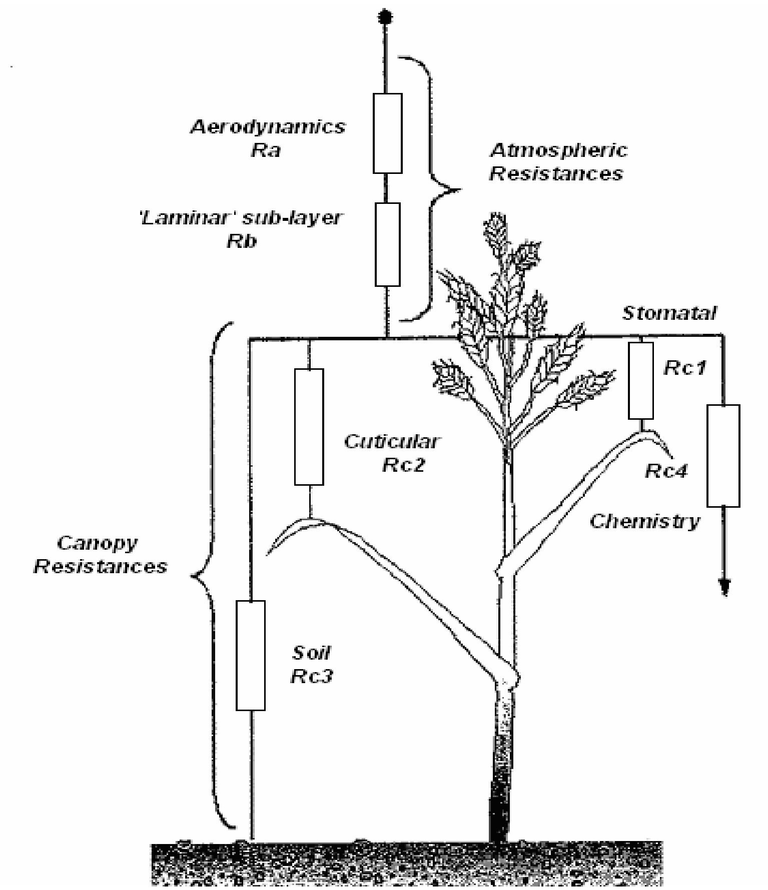

Fig. 1. Resistance diagram to show the effects of atmospheric and surface processes on pollutant deposition to terrestrial surfaces

Lee et al. (2004) demonstrated the use of tolerant plants to restore a coastal forest ecosystem severely damaged by air pollutants discharged from an industrial complex in two industrial cities of Korea. Further, results from transplant tests indicated that a field survey was the most reasonable method for the selection of tolerant plants to restore a pollution-damaged ecosystem. There are many plant species which fulfill these criteria and are useful ecosystem indicators. Any alteration in them has implications for the whole ecosystem. Accordingly, other studies have also acknowledged the possibility of using plants as an indicator to monitor air quality (Angold 1997; Loppi et al. 1997; Beckett et al. 1998; Roy and Sharma 1998; Freer et al. 2004; Santitoro et al. 2004). Hence, use of plant, as an indicator "device" to provide information on the toxicity of pollutants, is an inexpensive method, and can act as an early-warning indicator of deteriorating air quality.

A number of air pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ozone (O_3), peroxyacetyl nitrate (PAN), halogens and acid rain can onset early visible damage on plants. Hence, plants offer an excellent alarm system for detecting the presence of excessive concentrations of these pollutants and often provide the very first evidence on polluted air. Plant responses, characteristic visible foliar symptoms in particular, have long been used as indicators of air pollutants. In additions, the amount of metal accumulation has also been used as a bioindicator. This chapter considers the potential of plants as a phytoindicator/phytomonitor for management of air quality. A section of this chapter also outlines the role of plants in fighting indoor air pollution.

2. Plants as Bioindicators of Air Pollutants

2.1 Bioindicators for Sulfur Dioxide (SO_2)

Sulfur dioxide (SO_2) is a major pollutant in the atmosphere, especially in developing countries. Common sources of SO_2 include power plants, fossil-fuel furnaces, oil refineries, copper and iron smelters. The exposure of succulent, broad-leaved plants to SO_2 and its by-product sulfuric acid (H_2SO_4) usually results in dry, papery blotches colored tan, straw or even white, and turn to interveinal browning or necrosis. However, the leaf veins remain green. Young and mid-aged plants and leaves are more sensitive. Exposure to 0.5 ppm for 4 hours or 0.25 ppm for 8 hours may be injurious to some crops which may show symptoms as far as 50 km from its source. Plants are more sensitive to SO_2 during periods of bright sun, high relative humidity, and adequate plant moisture during the late spring and early summer.

Many plants are known to be injured by SO_2 under natural and experimental exposure conditions (Fig. 2). If SO_2 injury is suspected, one can check nearby, more sensitive crops, such as alfalfa, beans, beets, buckwheat, soybean, and sunflower, or sensitive weeds, such as pigweeds, ragweed and morning glory. In the National Monitoring Network of The Netherlands, alfalfa (*Medicago sativa*) and buckwheat (*Fagopyrum esculentum*) were used for monitoring the effects of SO_2 (Posthumus 1984). DeSloover and LeBlanc (1968) developed an Index of Atmospheric Purity (IAP), based on mathematical formula that correlated the lichen and bryophyte vegetation of an area with the air quality around urban areas or point sources of SO_2.

2.2 Bioindicators for Fluorides

Fluorides are compounds containing the elemental fluorine (F). Fluorides are produced by glass, aluminum, pottery, brick and ceramic industries and by refineries, metal ore smelters, and phosphate fertilizer plants. The typical injury by gaseous or particulate fluorides is either a yellowish mottle to a wavy, red-

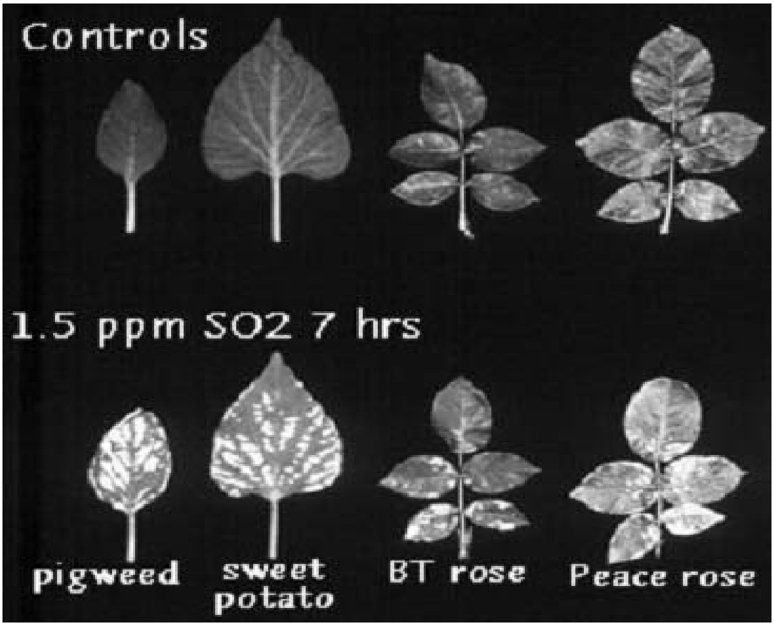

Fig. 2. Effect of SO_2 on several species, under controlled exposure of SO_2 (Source: University of Newcastle, UK)

dish or tan "scorching" at the margin or tips of the broad-leaved plants or a "tipburn" of grasses and conifers. Accumulated leaf-fluoride concentrations of 20 to 150 ppm often injure sensitive plants, although resistant varieties and species of plants will tolerate leaf concentrations of 500 to 4,000 ppm or more without any visible injury. Gladiolus (*Gladiolus hortulanus*) is the most widely used plant for biomonitoring fluoride (Manning and Feder 1980). A 4-week exposure of susceptible *Gladiolus hortulanus* to an air concentration of 0.0001 ppm, or less than 24 hours at 10 ppb, produces leaf concentrations of 150 ppm and definite tissue necrosis.

2.3 Bioindicators for Chlorides

Like fluorides, chlorides are compounds containing the elemental chlorine (Cl). Hydrogen chloride (HCl) and chlorine (Cl_2) are emitted from the stacks of glassmaking industries and refineries. These can be also produced by incineration and spillage, such as chlorine tanker storage tanks. Injury caused by chlorine is similar to that caused by SO_2 and fluorides, in that it is marginal and interveinal. On broad-leaved plants, necrotic, bleached, or tan to brown areas tend to be near the leaf margins, tips, and between the principal veins. Middle-aged or older ones are more susceptible that the young ones. Conifers may show tipburn on the current seasons. Susceptible plants, when exposed for 2 hours or more at concentrations of chlorine ranging from 0.1 to 4.67 ppm, show injury symptoms. Chlorine-injured vegetation is often observed near swimming pools, water-purification plants, and sewage-disposal facilities. Grasso et al. (1999) reported the capacity of lichens to accumulate atmospheric contaminators like, halides and particulate matters linked to volcanic activity in Italy: Mount Etna and Vulcano Island.

2.4 Bioindicators for Ethylene (Ethene)

Ethylene (H_2C-CH_2) is a known and important plant-toxic air pollutants. Ethylene is one of the many products of auto, truck, and bus exhaust. Ethylene also results from the incomplete combustion of coal, gas and, oil for heating and is a by-product of polyethylene manufacture. Ethylene (H_2C-CH_2) modifies the activities of plant hormones and growth regulators, which affect developing tissues and normal organ development, without causing leaf-tissue collapse and necrosis (Abeles and Heggestad 1973). Injury to broad-leaved plants occurs as a downward curling of the leaves and shoot (epinasty), followed by a stunting of growth. Posthumus (1983) suggested the use of petunia (*Petunia axilliaris hybrida*) as a bioindicator plant for H_2C-CH_2 in The Netherlands. Pleijel et al. (1994) used potted petunia (*Petunia hybrida*), placed at distances 10, 20, 40, 80 and 120 m from a motorway with approximately 30,000 vehicles/day, as an indicator for ethylene in Sweden in 1989. The result showed that the petunia flowers were significantly smaller on plants closer to the motorway that those at distance. Furthermore, the abortion rate of flower buds of plants closer to motorway was more frequent and the ripening of fruits was also high near motorway. Thus, the authors inferred from the survey that ethylene (H_2C-CH_2) concentrations were high enough to influence the petunia reproductive structures, close to the motorway.

2.5 Bioindicators for Ozone (O_3)

Ozone, a molecule (O_3), formed by three atoms of oxygen, is a photochemical oxidant that disrupts photosynthetic and metabolic functions. It is probably the most important phytotoxic air pollutant in the troposphere. Ozone is brought down to ground level by vertical winds from the stratosphere during electrical storms. But the most important mechanism of ozone formation in the tropospheric atmosphere is reaction of NO_x and hydrocarbons (HC) in presence of sunlight. O_3 is a widespread air pollutant in the industrialized countries (Stockwell et al. 1997). Leaf symptoms to ozone exposure are termed “stippling” or “speckling” characterized by numerous tiny dots on the upper leaf surface. On the other hand, long-term exposure to near-ambient ozone levels may lead to chlorotic symptoms or may reduce photosynthesis and crop yield without visible injury (Heath and Taylor 1997; Pell et al. 1997). Injury occurs mostly in the afternoon and the least at night.

The ozone sensitivity of plant species and cultivars varies greatly. There are some excellent bioindicator plant species that have been used widely to detect O_3 in the lower atmosphere. For example, the tobacco (*Nicotiana tabacum*) cultivars Bel-W3 (super-sensitive to ozone) and Bel-B (ozone-tolerant) have been used as ozone biomonitor and control, respectively, for three decades. This has greatly contributed to the awareness of people to recognize ozone as a pollutant (Heggestad 1991). Susceptible tobacco plants are injured when concentrations of ozone exceed 0.04 ppm. Further detail on tobacco, as an indicator plant for ozone, is considered later as an example. Morning glory (*Ipomoea violacea*) in Japan (Nouchi and Aoki 1979) and clover in Sweden (Karlsson et al. 1995) have also been reported as indicator plants for O_3. Reduction in growth of radish (*Raphanus sativus*) has been also observed as an indicator of ozone in Japan and Egypt (Izuta et al. 1993; Hassan et al. 1995). Several other plant species are also known as bioindicators of ozone exposures. Observations of symptoms from an open-top exposure chamber investigation in central Pennsylvania have confirmed that black cherry, yellow poplar, white ash, common milkweed, spreading dogbane, and blackberry were sensitive to ambient ozone exposures (Skelly 2000).

2.6 Tobacco

Ozone injury to tobacco is called weather fleck (Fig. 3). This symptom was first observed in 1959 (Heggestad and Middleton 1959). Tobacco (*Nicotiana tabacum*) is known to be particularly sensitive to ozone and the ozone-sensitive tobacco cultivar Bel-W3 has been widely used as biomonitor of tropospheric ozone (Heggestad 1991). Furthermore, they observed that the cultivar Bel-W3, developed from progeny of two plants, showed pergament-like lesions two to three times larger than those typically associated with ozone injury in cigar wrapper tobacco (Heggestad 1991). In contrast, the genetically related cultivar Bel-B was visibly unaffected by ambient ozone levels (Heggestad 1991; Langebartels et al. 1991). The "classical" ozone symptoms in tobacco cultivar Bel-W3 plants occur as sharply defined dot-like lesions on the adaxial side of the leaf resulting from the death of a group of palisade cells (Loreto et al. 2001). In a recent study, Nali et al. (2004) surveyed the use of vascular plants for the bioindication of tropospheric ozone in the area of Pisa (Tuscany, Central Italy). They observed that with the exposure of photochemical ozone surpassing 100 ppb (maximum hourly means) during the warm season, supersensitive tobacco cultivar Bel-W3 confirmed the value of detailed, cost-effective, monitoring surveys. Trials with clover clones demonstrated that sensitive plants underwent severe biomass reduction in the current ozone regime. Therefore, a set of tobacco plant species: Bel-W3 and Bel-B, as sensitive and tolerant cultivars, would be highly recommended for bioindication of ozone.

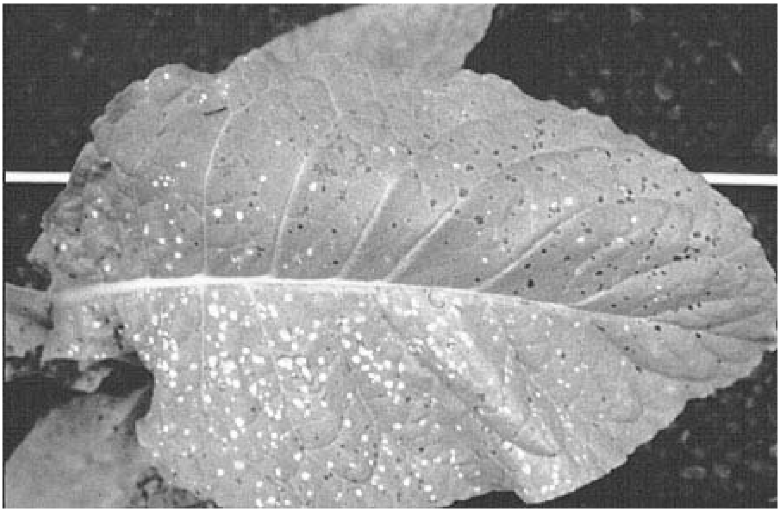

Fig. 3. Necrotic lesions on tobacco BEL-W3 leaves after growth at ambient ozone concentrations (Source: NCSU, Raleigh)

2.7 Bioindicators for Peroxyacetyl Nitrate (PAN)

Another photochemical oxidant is peroxyacetyl nitrate (PAN). After ozone, it is the most phytotoxic air pollutant. Like ozone, PAN is produced when sunlight reacts with various exhaust gases. PAN causes leaves to develop bands, blotches, bronzed and silvery areas. In some plants, such as petunia, pinto bean, tomato, and tobacco, the collapse may be through the entire thickness of the leaf blade. Pre-mature senescence and defoliation may also occur. PAN is most toxic to small plants and young leaves. Exposure to 0.01 to 0.05 ppm for one hour induces symptoms in susceptible plants. In the early 1940s, in Los Angeles basin, plants, such as romaine lettuce (*Lactuca sativa*), Swiss chard (*Beta chilensis*) and annual blue grass (*Pao annua*) were identified as bioindicators of PAN even when PAN had not yet been chemically identified (Manning and Feder 1980). Petunia plants are also known to be highly sensitive to PAN. But the sensitivity of petunia varies among cultivars and, in general, cultivars with white flower are more sensitive to PAN than those of blue or red flowers.

3. Phytoremediation and Urban Air Quality Management

Natural and planted vegetation are an efficient sink for various air pollutants including nitrogen oxides (NO_x) (Yunus et al. 1996), carbon dioxide (CO_2) (Pacala et al. 2001) and polycyclic aromatic hydrocarbons (PAHs) (Simonich and Hites 1994, 1995). Several other investigations too proposed that the plants should be utilized to reduce pollutant concentrations in the atmosphere (Hill 1971; Okano et al. 1988; Simonich and Hites 1994, 1995; Weber et al. 1995; Salt et al. 1998). Poor air quality has brought attention to trees as air pollution remedies since trees/plants directly absorb carbon dioxide in their life-dependent process, photosynthesis.

Plants play an important role in the mitigation of highly polluted atmosphere and extreme climates in urban and semi-urban areas. Pollutants in urban areas are of myriad types and distributed unevenly, as shown by some studies (Pfeffer 1994; Raaschou et al. 1995). Street/park trees in urban areas can be very helpful in mitigation of harmful pollutants and chemicals, including heavy metals from the environment (Pfeffer 1994; Raaschou et al. 1995). Removal of airborne pollutants is done by the process of respiration. During photosynthesis, plant intakes CO_2 simultaneously with several other pollutants, such as nitrogen oxides (NO_x), airborne ammonia, sulfur dioxide (SO_2), and ozone (O_3), that is also a part of the smog and greenhouse gases, through its stomata (Bergmann et al. 1995; Singh et al. 1995; Lea 1998; Morikawa et al. 1998; Wellburn 1998). Once inside the leaf, gases diffuse into the spaces between the cells of the leaf to be absorbed by water films or chemically altered by the plant tissues. Street trees in the urban areas are particularly important for this due to their close proximity to vehicles, the major source of air pollutants.

Plants also reduce air pollution by intercepting particulate matter (PM), and aerosols and retaining them on the leaf surface by process of *dry deposition*. Leaf surfaces are most efficient at removing pollutants that are water-soluble including SO_2, NO_2 and O_3. Pollutant removal rates are the highest when vegetative surfaces are wet or damp; these conditions can increase removal rates ten-fold because the entire tree surface is available for the pollutant uptake. A number of field measurements have suggested that the vegetation can significantly reduce their adverse effects through their ability to capture pollutant particles (Nasarullah et al. 1994; Beckett et al. 1998; Roy and Sharma 1998). In a more recent study, Freer et al. (2004) presented relative deposition velocities and capture efficiencies of five species used widely in woodland of urban and sub-urban areas of Europe i.e. oak (*Quercus petraea*), alder (*Alnus glutinosa*), ash (*Fraxinus excelsior*), sycamore (*Acer pseudo-platanus*) and Douglas fir (*Pseudotsuga menziesii*), and two species being used increasingly in semi-arid regions, i.e. weeping fig (*Ficus nitida*) and Eucalyptus (*Eucalyptus globulus*). The measurements were made at three wind speeds, and deposition velocities and capture efficiencies were compared with those published for other tree species. It was found that the values of deposition velocity ranging from 0.1 to 0.3 cm/s at a wind speed of 3 m/s to maximum values of 2.9 cm/s at 9 m/s wind speed. Further, the authors noticed that species with more complex stem structure and smaller leaves had greater deposition velocities. Such data sets can be used in the models to guide species choice and planting design in order to maximize particle removal from the urban air. It is also clear that species choice, planting design and location relative to pollution source are critical in determining the effectiveness of particle capture by trees.

Plants remove (sequester) carbon from the atmosphere through photosynthesis, extracting carbon dioxide from the air, separating the carbon atom from oxygen, and returning oxygen to the atmosphere (Pacala et al. 2001). Plant's ability to offset carbon emissions is determined by average size, canopy cover, health, and age, but larger tress can help in lowering annual carbon emissions by 2 to 3% in the atmosphere. Generally, trees are comprised of 45% carbon, 50% water, and 5% minerals, but these constituents vary from species to species.

Higher urban temperatures also accelerate the production of smog, of which ozone is a major component causing respiratory and other health problems. One of the major causes of smog is "heat-island effect", caused by the internal build-up of heat in cities from incoming solar energy absorbed onto concrete and asphalt, such as roads, parking lots, and buildings (Voogt and Oke 1989). This is further compounded by emissions from vehicles, houses and heating. Vegetation in urban areas helps to mitigate air quality problem by reducing temperature-dependent production of air pollutants, such as, ozone, VOCs and others (Taha 1997). Tree species strategically planted to shade homes can generate about 10 to 50% savings in cooling expenses depending upon tree type, location, and climatic variation. This not only reduces the amount of carbon-based fuels used, but also attenuate emissions that reduce air quality. Improvement in the air quality can be expected, if trees can absorb more air pollutants close to the pollutant sources and thus the number of exceedance days can be reduced. Nevertheless, species choices, planting design and location relative to pollution sources are necessary requirements for the phytoremediation of urban air quality. Mixed plantings should be planned, with the more susceptible plants acting as bioindicators for early-warning of deteriorating air quality and tolerant ones for amelioration of pollution level.

4. Phytoremediation and Indoor Air Quality (IAQ)

Air pollution is not confined to outdoor environment in cities, urban areas and industrial sites only. Now one's home itself could be a potent source of potentially harmful chemicals. "Energy crisis" of seventies, resulted in growing demand of airtight and insulated buildings to conserve energy. An unintended effect of this improved energy efficiency was poor indoor air quality (IAQ) because of airtight buildings hampering the circulation of airflow. Most buildings use recirculated air and mix it with minimum amount of fresh air being brought into the buildings through an outside duct for building ventilation. As a result, more and more buildings have indoor air quality (IAQ) problems due to building-up of hazardous pollutants and chemical compounds released from building materials and furnishings. This chemically polluted indoor environment has been related to symptoms of illness, known as the "sick house syndrome". The pollutants most widely present in indoor environment are: carbon monoxide (CO), nitrogen oxides (NO_x), undesirable products of burning tobacco and wood, formaldehyde, volatile organic compounds (VOCs), including chemicals like, toluene, xylene, ethylbenzene and chloropyrifos. Indoor air pollution has become a serious public health concern. This has fuelled growing demand for healthier indoor air, to which health professionals, architects, researchers and housing industry have made beginning to respond.

It is well acknowledged that plants are known for their ability to remove air pollutants from outdoor environment. They absorb carbon dioxide (CO_2) and significant amounts of harmful gases from the air and release oxygen as a part of photosynthetic process. Over the past few years, studies have shown that house plants have been able to reduce levels of some chemicals in the laboratory experiments. Many common house plants and blooming potted plants help fight against indoor air pollution (Wolverton et al. 1984; Wolverton et al. 1985). “Indoor” potted-plants can remove airborne contaminants, such as volatile organic compounds (VOCs), over 300 of which have been identified for indoor air pollution. Studies have shown that many house plants can absorb benzene, formaldehyde, trichloroethylene and other VOCs, (Wolverton and Wolverton 1993; Wolverton 1997; Orwell et al. 2004). The foliage of indoor plants is also capable of extracting particulate matters (PM) from the air. In an experiment, Lohr and Pearson (1996) reported that the presence of foliage plants in interior spaces changed particulate matter (PM) accumulation: accumaltion was lower in both rooms when plants were present than when plants were absent. In particular, vegetation with rough surfaces with fine hairs or raised veins is more effective in intercepting PM than smooth vegetation. Plant roots can also absorb some pollutants and render them harmless in the soil.

In a study sponsored by National Aeronautics and Space Administration (NASA), spider plants (*Chlorphytum elatum*) were placed in closed chambers with 120 ppm of CO or 50 ppm of NO_2 (Wolverton et al. 1985). After 24 hours, spider plants removed 96% of CO and 99% of NO_2. Experiments with Golden pothos plants (*Epipremnum aureum*) showed that 75% of CO was removed after 24 hours. Another study, conducted jointly through NASA and the Associated Landscape Contractors of America (ALCA), investigated the use of common indoor plants to provide a natural way to combat "Sick Building Syndrome" (Wolverton et al. 1989). The chemicals screened for the removal were benzene, formaldehyde and trichloroethylene. The results of these tests suggested:

- Low-light-requiring house plants with activated carbon plant filters have potential for improving IAQ.
- The plant root-zone is an effective area for removing VOCs. (maximum air exposure to plant root-soil area for best filtration).
- Use of activated carbon filter should be part of the house plant/air-cleaning plan.

However, NASA studies were conducted in a closed chamber climate controlled environment with activated carbon, air blown through the soil and single contaminant release. The purpose of their studies was to see if plants could be used for space habitation; nevertheless, the results provided impetus to use foliage plants in offices and other workplaces to improve the quality of indoor air.

Plants need sunlight in order to convert CO_2 into oxygen by the process of photosynthesis. From the perspective of indoor environment, it would be very helpful to study some common house plants that need less light or no light for photosynthesis process. Raza et al. (1995) evaluated the status of indoor air quality of a hospital using several plants that do not need light. They found that *Apicra deltoidea* is the most effective, followed by *Sedum pachyphyllum*, in converting carbon dioxide into oxygen at night when there is no sunlight.

Below is the list of most effective plants with large leaf surface area to be used in removing pollutants like, formaldehyde (Source: UF/IAS):

- Heart-leaf philodendron (*Philodendron scandens*)
- Elephant ear philodendron (*Philodendron domesticum*)
- Green spider plant (*Chlorphytum elatum*)
- Lacy tree philodendron (*Philodendron selloum*)
- Golden pothos (*Epipremnum aureum*)
- Chinese evergreen (*Aglonema modestum*)
- Mini-Schefflera (*Bassaia arboricola*)
- Peperomia (*Peperomia obtusifolia*)
- Peace lily (*Spathiphyllum clevelandii*)
- Corn plant (*Dracaena fragrans 'massangeana'*)
- Snake plant (*Sansevieria traifasciata*)

To some extent, these plants can also be used against pollutants like, benzene and trichloroethylene. Most of the house plants listed above are commonly found in tropical and sub-tropical forests, where they received light filtered through the branches of taller trees. Because of this, their leaf photosynthesizes efficiently under relatively low light conditions, which, in turn, allows them to process gasses in the air efficiently.

However, careful selection of indoor plants is necessary, if anyone suffers from exposure to molds, pollen, odors or dust. House plants also add moisture to the indoor environment. Molds can grow in the soil of the plant and release spores into the air. This can have negative effects on comfort and health of the occupants. Wolverton (1997) has detailed the role of house plants in fighting indoor air pollution in his book.

5. Conclusion

Air pollution has both direct and indirect impacts on the plant life. Some plants are very sensitive to the air pollution. If there is any injury caused by air pollution, the plant shows an appropriate response. The early recognition of pollutant damage to plants, notably characteristic visible foliar symptoms, acts as an alarm for toxic dangers to humans and their environment. Hence, the bioindicator method indicates directly whether the ambient concentration of a pollutant is harmful to biological tissues, and reveals the synergetic and antagonistic effects of multiple pollutants of the environment. A suitable bioindicator plant must be sensitive to a specific pollutant and respond proportionally to the pollutant or dose; be native or adaptable to the region and abundant presence; and be tolerant to pests and diseases. Bioindicator/biomonitoring method provides a relatively low-cost and easy method of environmental surveillance compared to high tech measuring methods.

Despite being novel technology for environmental monitoring, the great potential of bioindicators is often confronted with difficult questions of methodology how to use "living measuring instruments". The effects of environmental load can not always be clearly differentiated from natural stress factors. Lack of practical experience with certain bioindicators makes interpretation of findings very difficult, especially if, no comparable pollutant measurements are available. Hence, efforts should be made to develop standardized indicator species that will show known, reliable dose-response relationships with any gaseous pollutants and mixture under various environmental conditions.

It can be concluded that a more integrated and detailed approach, a combination of physical and chemical methods together with indicator plants, is most reliable means of monitoring air quality for protecting human health and the environment. Phytoremediation of air pollutants using street/park trees with abundant foliage helps to a greater extent in improving urban air quality. They are capable of removing pollutants, like gases and particulate matters; reduce energy expenditures and lower air temperatures. Similarly, many common house plants and blooming potted plants help fight against pollution in indoor environment. They scrub significant amount of toxic pollutants and chemical compounds from air and render them harmless. Systematic studies of responses of plants in indoor and outdoor environment would greatly increase our understanding of plants as biological indicators of air quality. Bioindicator method provides a novel and cost-effective technology to visualize and monitor environmental air pollution keeping public health in mind.

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References

Abeles FB, Heggestad HE (1973) Ethylene: an urban air pollutant. J Air Pollut Contr Assoc 23:517-521

Alfani A, Maisto G, Iovieno P, Rutigliano FA, Bartoli G (1996) Leaf contamination by atmospheric pollutants as assessed by elemental analysis of leaf tissue, leaf surface deposit and soil. J Plant Physiol 148:243-248

Alscher RG, Wellburn AR (1994) Plant responses to the gaseous Environment. Chapman & Hall, London

Angold PG (1997) The impact of a road upon adjacent vegetation: effects on plant species composition. J Appl Ecol 34:409-417

Beckett KP, Freer PH-S, Taylor G (1998) Urban woodlands: the role in reducing effects of particulate pollution. Environ Poll 99:347-360

Bell JNB, Treshow M (2002) Air Pollution and Plant Life, 2nd Edition. John Wiley and Sons, Ltd

Bergmann E, Bender J, Weigel HJ (1995) Growth responses and foliar sensitivities of native herbaceous species to ozone exposures. Water Air Soil Poll 85:1437-1442

Bleasedale JKA (1973) Effects of coal-smoke pollution gases on the growth of ryegrass (*Lolium perenne* L.). Environ Poll 5:275-285

Canas MS, Carreras HA, Orellana L, Pignata ML (1997) Correlation between environmental conditions and foliar chemical parameters in *Ligustrum lucidum* Ait. Exposed to urban pollutants. J Environ Manag 49:167-181

DeKok LJ, Stulen I (1998) Responses of Plant metabolism to Air Pollution and Global Change. Backhuys, Leiden, The Netherlands

DeSloover J, LeBlanc F (1968) Mapping of atmospheric pollution on the basis of lichen sensitivity. In: Misra R, Gopal B (eds) Proc Symposium on Recent Advances on Tropical Ecology, pp 42-56

Freer PH-S, El AA-K, Taylor G (2004) Capture of Particulate Pollution by Trees: A Comparison of Species Typical of Semi-Arid Areas (*Ficus nitida* and *Eucalyptus globulus*) with European and North American Species. Water Air Soil Pollut 155:173-187

Grasso MF, Clocchiatti R, Carrot F, Deschamps C, Vurro F (1999) Lichens as bioindicators in volcanic areas: Mt. Etna and Vulcano Island (Italy). Environ Geol 37:207-217

Harward M, Treshow M (1975) Impact of ozone on the growth and reproduction of understorey plants in the aspen zone of western USA. Environ Conserv 2:17:23

Hassan IA, Ashmore MR, Bell JNB (1995) Effect of ozone on radish and turnip under Egyptian field conditions. Environ Poll 89:107-114

Heath RL, Taylor GE (1997) Physiological processes and plant responses to ozone exposure. In: Sandermann H, Wellburn AR, Heath RL (eds) Forest Decline and Ozone: a Comparison of Controlled Chamber and Field Experiments, Ecological Studies, 127, Springer, Berlin, pp 317-368

Heck WW, Taylor OC, Tingey DT (1988) Assessment of Crop Loss from Air Pollutants. Elsevier Applied Science, London and New York

Heggestad HE (1991) Origin of Bel-W3, Bel-C and Bel-B tobacco varieties and their use as indicators of ozone. Environ Poll 74:264-291

Heggestad HE, Middleton JT (1959) Ozone in high concentrations as cause of tobacco leaf injury. Science 129:208-210

Hill AC (1971) Vegetation: a sink for atmospheric pollutants. J Air Pollut Contr Assoc 21:341-346

Hutchinson TC, Meema GHM (1987) Effects of atmospheric pollutants on forests, wetlands and agricultural systems. Springer-Verlag, Berlin

Izuta T, Miyake H, Totsuka T (1993) Evaluation of air-polluted environment based on growth of radish plants cultivated in small-sized open-top chambers. Environ Sci 2:25-37

Karlsson GP, Sellden G, Skarby L, Pleijel H (1995) Colver as an indicator plant for phyotoxic ozone concentrations: visible injury in relation to species, leaf age and exposure dynamics. New Phytol 129:355-365

Langebartels C, Kerner K, Leonardi S, Schraudner M, Trost M, Heller W, Sandermann H (1991) Biochemical plant responses to ozone: I. Differential induction of polyamine and ethylene biosynthesis in tobacco. Plant Physiol 95:882-889

Lea PJ (1998) Oxides of nitrogen and ozone: can our plants survive? New Phytol 139:25-26

Lee CS, Lee KS, Hwangbo JK, You YH, Kim JH (2004) Selection of Tolerant Plants and Their Arrangement to Restore a Forest Ecosystem Damaged by Air Pollution. Water Air Soil Poll 156:251-273

Lohr VI, Pearson C-M (1996) Particulate matter accumulation on horizontal surfaces in interiors: Influence of foliage plants. Atmos Environ 30:2565-2568

Loppi S, Nelli L, Ancora S, Bargagli R (1997) Passive monitoring of trace elements by means of tree leaves, epiphytic lichens and bark substrate. Environ Monitor Assess 45:81-88

Loreto F, Mannozzi M, Maris C, Nascetti P, Ferranti F, Pasqualini S (2001) Ozone quenching properties of isoprene and its antioxidant role in leaves. Plant Physiol 126:993-1000

Manning WJ, Feder WA (1980) Biomonitoring air pollutants with plants. Applied Science Publishers, London

Morikawa H, Higaki A, Nohno M, Takahashi M, Kamada M, Nakata M, Toyohara G, Okamura Y, Matsui K, Kitani S, Fujita K, Irifune K, Goshima N (1998) More than a 600-fold variation in nitrogen dioxide assimilation among 217 plant taxa. Plant Cell Environ 21:180-190

Nali C, Crocicchi L, Lorenzini G (2004) Plants as indicators of urban air pollution (ozone and trace elements) in Pisa, Italy. J Environ Monitor 6:636-645

Nasrullah M, Tatsumoto H, Misawa A (1994) Effect of roadside planting on suspended particulate matter concentration near road. Environ Techno 15:293-298

Nouchi I, Aoki K (1979) Morning glory as a photochemical oxidant indicator. Environ Poll 18:289-303

Okano K, Machida T, Totsuka T (1988) Absorption of atmospheric NO_2 by several herbaceous species: estimation by the ^{15}N dilution method. New Phytol 109:203-210

Orwell RL, Ronald L, Wood RL, Tarran J, Torpy F, Burchett MD (2004) Removal of Benzene by the Indoor Plant/Substrate Microcosm and Implications for Air Quality. Water Air Soil Poll 157:193-207

Pacala SW, Hurtt GC, Baker D, Peylin P, Houghton RA, Birdsey RA, Heath L, Sundquist GT, Stallard RF, Ciais P, Moorcroft P, Caspersen JP, Shevliakova E, Moore B, Kohlmaier G, Holland E, Gloor M, Harmon ME, Fan SM, Sarmiento JL, Goodale CL, Schimel D, Field CB (2001) Consistent land-and atmosphere-based U. S. carbon sink estimates. Science 292:2316-2320

Pell EJ, Schlagnhaufer CD, Arteca RN (1997) Ozone-induced oxidative stress: Mechanisms of action and reaction. Physiol Plant 100:264 273

Perkins HC (1974) Air Pollution. McGraw-Hill Book Co., New York

Pfeffer HU (1994) Ambient air concentrations of pollutants at traffic-related sites in urban areas of North Rhine-Westphalia, Germany. Sci Tot Environ 146/147:263-274

Phillips DH (1980) Quantitative aquatic biological indicators. Applied Science, London

Pleijel H, Ahlfors A, Skarby L, Pihl G, Sellden G, Sjodin A (1994) Effects of air pollutant emissions from a rural motorway on *Petunia* and *Trifolium*. Sci Tot Environ 146/147:117-123

Posthumus AC (1983) Higher plants as indicators and accumulators of gaseous air pollution. Environ Monitor Assess 3:263-272

Posthumus AC (1984) Monitoring levels and effects of air pollutants. In: Treshow M (ed) Air Pollution and Plant Life, John Wiley and Sons, Chichester, pp 73-95

Posthumus AC (1985) Plants as indicators for atmospheric pollution. In: Nurnberg HW (ed) Pollutants and their ecotoxicological significance, Wiley, London, pp 55-65

Raaschou O-N, Nielsen M-L, Gehl J (1995) Traffic-related air pollution: exposure and health effects in Copenhagen street cleaners and cemetery workers. Arch Environ Health 50:207-213

Raza RH, Shylaja G, Gopal BV (1995) Different abilities of certain succulent plants in removing CO_2 from the indoor environment of a hospital. Environ Intern 21:465-469

Roose ML, Bradshaw AD, Roberts TM (1982) Evolution of resistance of gaseous air pollutants. In: Unsworth MH, Ormond DP (eds) Effects of gaseous pollutants in Agriculture and Horticulture, Butterworth, London, pp 379-409

Roy RK, Sharma SC (1998) Bioremediation of urban pollution by orientation of landscaping. Ind J Environ Health 40:203-208

Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Mol Biol 49:643-668

Santitoro A, Aprile GG, Baldantoni D, Bartoli G, Alfani A (2004) Trace Element Analyses in an Epiphytic Lichen and its Bark Substrate to Assess Suitability for Air Biomonitoring. Environ Monitor Assess 98:59-67

Simonich SL, Hites RA (1994) Importance of vegetation in removing polycyclic aromatic hydrocarbons from the atmosphere. Nature 370:49-51

Simonich SL, Hites RA (1995) Organic pollutant accumulation in vegetation. Environ Sci Techno 29:2905-2914

Singh N, Yunus M, Srivastava K, Singh SN, Pandey V, Misra J, Ahmad KJ (1995) Monitoring of auto exhaust pollution by roadside plants. Environ Monitor Assess 34:13-25

Singh SN (2000) Trace Gas Emissions and Plants. Kluwer Academic Publishers, The Netherlands

Skelly JM (2000) Tropospheric ozone and its importance to forests and natural plant communities of the Northeastern United States. Northeastern Naturalist 7:221-236

Stockwell WR, Kramm G, Scheel H-E, Mohnen VA, Seiler W (1997) Ozone formation, destruction and exposure in Europe and the United States. In: Sandermann H, Wellburn AR, Heath RL (eds) Forest Decline and Ozone: a Comparison of Controlled Chamber and Field Experiments, Ecological Studies, 127, Springer, Berlin, pp 1-38

Taha H (1997) Urban Climates and Heat Islands: Albedo, Evapotranspiration, and Anthropogenic Heat. Energ Build - Special Issue on Urban Heat Islands 25:99-103

Treshow M (1984) Air Pollution and Plant Life. John Wiley and Sons, Chichester

Treshow M, Anderson FK (1991) Plant Stress from Air Pollution. John Wiley and Sons, Chichester
Voogt JA, Oke TR (1989) Complete Urban Surface Temperatures. J Appl Meteor 36:1119-1132
Weber P, Nubbaum S, Fuhrer J, Gfeller H, Schlungger U, Brunold P, Rennenberg H (1995) Uptake of atmospheric $^{15}NO_2$ and its incorporation into free amino acids in wheat (*Teitcium aestivum*). Physiol Plant 94:395-429
Wellburn AR (1998) Atmospheric nitrogenous compounds and ozone-Is NO_x fixation by plants a possible solution? New Phytol 139:5-9
Wolverton BC (1997) How to Grow Fresh Air: 50 Houseplants that Purify Your Home or Office. Penguin Books, New York. First published in UK as *Eco-Friendly Houseplants.* Weidenfeld & Nicolson, London, 1996
Wolverton BC, Wolverton JD (1993) Plants and Soil Microorganisms - Removal of Formaldehyde, Xylene and Ammonia from the Indoor Environment. J Missi Acad Sci 38:11-15
Wolverton BC, Johnson A, Bounds K (1989) Interior Landscape Plants for Indoor Air Pollution Abatement. NASA/ALCA Final Report, Plants for Clean Air Council, Davidsonville, Maryland.
Wolverton BC, McDonald RC, Mesick HH (1985) Foliage Plants for the Indoor Removal of the Primary Combustion Gases Carbon Monoxide and Nitrogen Oxides. J Missi Acad Sci 30:1-8
Wolverton BC, McDonald RC, Watkins EA Jr (1984) Foliage Plants for Removing Indoor Air Pollution from Energy-Efficient Homes. Econo Botan 38:224-228
Yunus M, Singh N, Iqbal M (1996) Global status of air pollution: an overview. In: Yunus M, Iqbal M (eds) Plant Response to Air Pollution, John Wiley, UK, pp 1-34