Protecting Horticultural Plants from Atmospheric Pollutants: A Review

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Atmospheric pollutants cause decreased yields, growth suppression and low product quality in both ornamental and vegetable crops, including petunias (23), begonias (45), snapdragons (1), onions (21), beans (70), cucumbers (53), radish (49), tomato (55) and several others (32). Fruit crops most widely injured are grapes (59) and citrus (69). Details of other sensitive plants have been discussed by Rich (57).

Annual crop loss due to air pollutants, in the United States, has been estimated at $500 million (30). This estimate is probably conservative since there are both obvious as well as latent forms of damage, and only the former would be reflected in the estimated crop loss value. Heggestad (31), for example, suggests that much of the plant damage resulting from air pollution is due to suppression of growth, which could be as much as 50% in certain crops. It has also been projected by Wood (71) that effective air pollution abatement is not likely for the next two decades. This is evidently supported by the recent relaxation, by the U.S. Environmental Protection Agency, of air pollution abatement standards previously established for industries. Such a relaxation has, in turn, resulted from the current energy shortage, and allows industries to use, for example, fuels with high sulfur levels.

In view of both current and anticipated heavy crop losses, there is the need for both long-term and short-term solutions in the protection of plants from air pollutant damage. The long-term approach will take the form of breeding or selecting cultivars that are either resistant to, or significantly tolerant of, air pollutants. Meanwhile, air pollutant damage to plants can be minimized through the use of chemical agents and certain cultural practices.

Air pollution injury to plants has been a subject of several reviews. In 1961, Middleton (51) reviewed general aspects of plant damage. Rich (57) emphasized growth and protection aspects, while Heck (28) reviewed factors influencing damage. More recently, Dugger and Ting (19) reviewed physiological and biochemical aspects of air pollution damage. Rich (57) reviewed some aspects of protection, particularly the early attempts with fungicides and related chemicals, as well as the use of certain inert surface-active materials. The present review will emphasize attempts to reduce injury by various means and agents and will cover broader groups of chemicals and also the edaphic, environmental and genetic aspects of protection.

Chemical protection

Fungicides. One of the earliest reports of chemical protection was that of Kendrick et al. (40) who demonstrated that plant injury caused by exposure of plants to ozonated gasoline or hexene-1 can be prevented with sprays or dusts of zinc ethylene bis dithiocarbamate (zineb), manganese ethylene bis dithiocarbamate (maneb), tetramethylthiuram disulfide (thiram), or ferric dimethyl dithiocarbamate (ferbam). In the same study, such fungicides as Bordeaux mixture, 2,3-dichloro-1,4-naphthoquinone (dichlone), or tetrachloro-p-benzoquinone (chloranil) did not effectively protect bean plants. In a subsequent report (38) covering field tests as well as laboratory experiments, the degree of protection was found to be directly related to the concentration of chemicals. Action of the chemical protectant was local and not systemic, suggesting the deactivation of oxidants at the leaf surface. Low concentrations of some recently developed fungicides may be even more effective than those used earlier. Seem et al. (61) have found that the systemic fungicide, α-2,4-dichlorophenyl-α-phenyl-5-pyrimidinemethanol (triarimol) suppressed ozone injury to 11-day old greenhouse- and growth chamber-grown bean plants. Foliar sprays at a concentration of 50 mg/liter resulted in a 4-fold reduction of injury. Protection was also obtained with as low as 2 μg/g soil. Two other systemic fungicides with commercial promise for chemical control of pollution damage are thiophanate ethyl (1,2-bis(3-ethoxycarbonyl-2-thioureido) benzene, and thiophanate methyl (1,2-bis(3-methoxycarbonyl-2-thioureido) benzene. Nearly complete protection from ozone injury to bean plants was achieved with 200 μg thiophanate ethyl per gram soil (62). Soil application of thiophanate methyl was not consistently effective, while foliar applications of both fungicides at the rate of 500 mg/liter resulted in significant reduction of injury.

Antioxidants. These are a heterogeneous group of chemicals which have been found to prevent oxidant damage to plants, principally by the inhibition of oxidative processes. These include simple reducing agents, commercial antioxidants, and specific antiozonants used in the rubber industry. Freebairn and Taylor (26) used ascorbic acid to protect a diversity of crops including beans, celery, romaine lettuce, petunias and citrus from leaf injury caused by polluted air of the Los Angeles area. Most species were partially protected, while a substantial protection in petunias was associated with increase in the number and weight of leaves. Oxidant damage to bean plants sprayed with 0.01 M potassium ascorbate was about 40% as great as damage to control plants. A reaction of ascorbic acid with the oxidants, at the leaf surface, was discounted since single applications of large amounts of ascorbic acid were not enough to prevent injury soon after application. It was later shown that both the potassium and calcium salts of ascorbic acid, when fed through the roots, protected bean plants from ozone injury (25). On purely experimental bases, protection of cucumber seedlings from injury expected at acute levels was found with a wide variety of chemicals, including hydrazine, indole, tryptophane and mescaline by Siegel (65). Protection was evident in increased survival of seedling populations and in reduced inhibition of hypocotyl section elongation. Ascorbic acid failed to provide appreciable protection in cucumber (65), but provided significant protection in beans (25) and petunias (26). The low effectiveness of ascorbic acid was attributed to the lack of specific effect on growth alterations, and also to possible autoxidation to dehydroascorbic acid (65). These reasons have been largely negated by the work with beans (25). The apparent conflict in these responses may be related to the differences in effective uptake of ascorbic acid supplied to the roots. It is, however, interesting to note that Dass and Weaver (17) also found ascorbic acid to be less effective than nickel-N-dibutyl dithiocarbamate in protecting bean plants. Under field conditions, manganous 1, 2-naphthoquinone-2-oxime protected tomato foliage from damage apparently caused by excessive atmospheric ozone (58). The similar cobaltous and manganous chelates of 8-quinolinol were also effective antiozonants. These chemicals were applied to cloth (at the rate of 405 mg/m^2) which was used in the same manner as in shade-grown tobacco. Compounds used as antiozonants in the rubber industry, for example the dialkyl-p-phenylenediamines, proved to be even more effective.

Growth regulators. Some growth regulators were studied in relation to air

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pollutant oxidants as early as 1954 (35). Such studies, however, were primarily concerned with the effects of pollutants on the activity of indoleacetic acid using *in vitro* biological systems (52), *Avena* coleoptile bioassays (35) and short-term seedling experiments (65). Under *in vitro* conditions, ozone inactivated indoleacetic acid, but it was not known if such an inactivation would be of significance in mature intact plants. In radish plants, Adedipe and Ormrod (3) found that ozone at 25 pphm for 4 hr had no effect on leaf weights of plants pre-treated with 30 mg/liter of 6-benylamine purine (BA), gibberellic acid (GA) or indoleacetic acid (IAA), but decreased leaf weight of control plants and of plants treated with (2-chloroethyl)-phosphonic acid (ethephon). In terms of radish root weight, however, ozone had no effect only in plants treated with BA. BA was thus found to be the most active of the growth regulators tested in the protection of plants from oxidant damage, both in terms of ozone-induced growth suppression and decrease in chlorophyll content of leaf. Lee (44) had earlier obtained increased ozone susceptibility with 6-furfurylaminopurine (kinetin), a cytokinin similar to BA. The apparent conflict could be due to differences in activity of specific cytokinins, or to the use of detached leaves (44), or to differential species response, or indeed, a combination of these factors. In bean plants, abscisic acid treatment of the primary leaves reduced ozone injury (24). Cathey and Heggestad have shown the protection of several lines of petunia from ozone damage (12) and of poinsettia plants from ozone and sulfur dioxide damage (13), with the use of growth retarding chemicals. Petunia plants which had been treated with foliar sprays of succinic acid-2,2-dimethylhydrazide (SADH) and 2,4-dichlorobenzyl tributylphosphonium chloride (phosfon) exhibited reduced injury in direct relation to chemical dosage (12). Addition of ascorbic acid and a wax coating (Folicote) to the spray solution increased the protection afforded by SADH. In poinsettia plants, α-cyclopropyl-α-(4-methoxyphenyl)-5-pyrimidine methanol (ancymidol) and (2-chloroethyl)trimethylammonium chloride (chlormequat) reduced visible injury induced by ozone and sulfur dioxide (13).

Edaphic and environmental factors

Mineral nutrition. The protection aspects of mineral nutrients are complex and varied. Generally, mineral nutrient levels that promote growth have been reported to also increase pollutant injury to crops. However, specific responses are dependent on the specific element and species under consideration.

One of the earliest reports on the influence of mineral nutrition is that of Brennan et al. (9) that the tip and margin burns characteristic of fluoride toxicity was minimum at deficient and at excessive levels of N. In mangels (10) the severity of injury resulting from ozonated hexene was significantly increased as the N level was increased. Spinach plants fumigated with peroxides derived from olefins showed 5-7 times as much damage when grown with abundant N supply as when grown under low or deficient N status (39). Growth suppression by ozone treatment of radish plants was also more severe at high than at low N levels (54).

Reports for P are not as straightforward as for N. In tomato, fluoride injury (9) and ozone toxicity (46) generally increased with increase in P supply. While P level had no significant effect on ozone-induced growth suppression in radish, high level of P accentuated phytotoxicity (54). In mangels and spinach (10) there were significant interactions of P with N and with K. Additions of P without K, or K without P, at the medium and high N levels produced poor top growth that was resistant to oxidant injury. When both P and K were added, however, top growth and severity of injury were significantly increased.

Both deficient and excessive amounts of Ca prevented flourine injury in tomato (9). When Ca was added to the substrate in concentrations above 40 ppm, its tendency to precipitate fluorine in the form of insoluble compounds within or around the roots further reduced the possibility of injury to foliage. This action of Ca appears to be a physico-chemical one, as was also obtained with lime foliar dusts and sprays in the protection of gladiolus from fluoride scorch (6), and of peaches from soft suture (7).

In tomato plants (47) increased sulfur level was associated with a greater degree of SO_2 susceptibility. In bean plants, however, Adedipe et al. (2) reported markedly lower ozone phytotoxicity at a high level (32 mg/liter) of sulfur than at the low level of 1.3 mg/liter. Increased SO_2 susceptibility at high S rates was apparently a result of cumulative toxicity since increased injury parallelled elevated foliar S absorption from both the nutrient solution and the SO_2 atmosphere. The protective action of high S against ozone injury, on the other hand, may have resulted from elevated amounts of sulfhydryl groups in the plant tissues, since several chemicals containing sulfhydryl groups had earlier been used as protective sprays (22).

Soil-Plant-Water Relations. Generally, plants grown under water stress conditions are tolerant of atmospheric pollutants, indicating that an increase in soil water, resulting in an increase in plant water status, also increases air pollutant injury. Early studies were carried out with tobacco (67, 69). According to Seidman et al. (63), injury to petunia and pinto bean plants from ozone and irradiated auto exhaust could be substantially reduced by withholding water from plants prior to exposure. In tomato (41), plants subjected to water stress resulting in a low relative leaf turgidity of 80% prior to ozone fumigation, were considerably protected from ozone injury. The effects were mainly restricted to soil-plant-water conditions prior to and during ozone treatment. In the study there was no significant growth reduction due to water stress. Ozone effects were therefore those related to tissue water contents *per se*, independent of growth. In related greenhouse studies by Stolzy et al. (66) on the relation of soil-oxygen diffusion rates to the susceptibility of tomato plants to ozone, low diffusion rates made the plants more resistant, and this effect was most noticeable when plant vigor was obviously impaired. Under field conditions, therefore, it is expected that crop loss resulting from air pollutant injury could be considerably reduced, if not prevented, by following a less frequent irrigation schedule (but not to the point of adversely affecting crop yield), or by temporarily withholding water supply during air pollution episodes (50). This has been supported by Rich (57) who observed that 1963 rainfall, averaging 2-5 inches below normal in the growing season, protected the Connecticut tobacco crop from oxidant injury.

Environmental factors. Air pollutant injury to plants is modified by several environmental factors, prominent among which are temperature, light and humidity (28, 29, 57). Generally, temperatures that promote good growth also predispose plants to greater damage (29, 37, 67). Kendrick et al. (39) obtained reduced sensitivity of spinach and lettuce at low temperatures. Ormrod et al. (54) reported greater ozone suppression of radish dry weight at 20/15°C (day/night) than at 30/25°. In a subsequent study (5) with radish in which the temperature used had no overall effect on plant growth, there was increased ozone sensitivity in terms of growth suppression at the lower growth temperature. Greatest susceptibility in this study was therefore not related to optimum temperature for growth in contrast to the response of many other species (16). Plants exposed to medium or high light intensity are also generally more sensitive to ozone (37). Air pollutant injury is also usually more severe at high than at low relative humidities (29). For example, foliar necrosis due to fluoride accumulation in gladiolus was more intense and occurred sooner in plants exposed at 80% than at 50% or 65% relative humidity (48), while plants at 30% were 3 times more resistant to SO_2 than those at 100% (64).

Postfumigation cultural conditions have not been extensively studied, and are generally considered to have little or no effect on the sensitivity of plants to specific phytotoxicants (28). More studies are indicating post-exposure effects of environmental factors. For example, according to Taylor et al. (68) a short exposure of pinto bean plants to PAN required a 2-4 hr 'postlight' period for injury development. Adedipe and Ormrod (5) have demonstrated that both the pre- and the postexposure temperature conditions determine overall ozone injury in 'Cherry Belle' radish plants.

Genetic tolerance

Knowledge of relative tolerance of horticultural plant species and cultivars to air pollutants is necessary for the recommendation of specific plant types for areas with high frequency of episodal concentrations of pollutants. Such information is also useful for the selection of genetic lines or accessions for breeding programs.

Several studies of species susceptibility and tolerance to ozone have been conducted (42). Symptoms vary with specific pollutants and with species (36). Of the vegetable crops, onions and tomatoes are the most widely studied. Tolerant cultivars include 'Downing Yellow Globe' and 'Autumn Spice' in onions (53), 'Polaris 135' cucumber and 'Superior' potato. In tomatoes it has been shown that there are wide differences in species sensitivity. The greatest sensitivity to ozone was observed in the accession *Lycopersicon pimpinellifolium* while the greatest level of tolerance was in *L. esculentum* (27). In cultivar studies, both Clayberg (14) and Reinert et al. (55) showed 'Heinz 1439' to be among the least sensitive to ozone; 'New Yorker' (14) and 'VF 145 B' were quite tolerant. 'Great Lakes' and 'Black-seeded Simpson' lettuce and 'Icicle' lettuce were the least sensitive (56). In field plantings, sweet corn hybrids were reported to show differential injury resulting from oxidant pollutants (11).

Of the ornamental plants, emphasis has been on bedding plants. In begonias, Leone and Brennan (45) found 'Red Comet' to be only moderately injured, while 'White Comet' was severely injured by ozone. Similarly, Adedipe et al. (1) reported 'Scarletta' to be more tolerant than 'White Taudenschon' to ozone and sulfur dioxide. It therefore appears that the red and pink begonias are generally more tolerant of pollutants than the white cultivars. Tolerant petunias include 'Canadian All Double Mixture' (1), and 'Capri' (12, 23). Many species of turfgrasses show differential susceptibility. Bentgrasses and annual bluegrass were most sensitive, while bermudagrass and zoysia were most resistant to ozone and sulfur dioxide (8). In the bentgrasses, 'Penncross' was most highly sensitive to ozone, but 'Kingstown Velvet' and 'Highland Colonial' showed significantly less injury.

Modes of genetic and acquired tolerances

In air pollutant injury, many aspects of plant metabolism may be impaired. While pollutant injury has been ascribed to several such physiological manifestations (19, 28, 57) the role of stomata appears to be important. That stomata have to be open for injury to occur has been demonstrated in a number of species, with several pollutants, particularly ozone (20, 33, 34, 42, 43) and sulfur dioxide (15), although the role of stomata in the control of PAN injury has been discounted (18).

Protection from air pollutant injury due to inherent characteristics of certain plant species and cultivars, and due to certain chemicals, is therefore largely a result of stomatal closure. The action of chemicals can be physical by way of thin films of solutions, or may be physiologically effected through the regulation of guard cell turgidity. In onion Engle and Gabelman (20) reported that the mechanism of resistance to ozone injury is that of stomatal closure. The guard cells of tolerant cultivars are so sensitive that they close and protect the plants, while they remain open in susceptible cultivars. Plants that have been made to acquire relative tolerance show similar stomatal behavior. Adedipe and Ormrod (4) used prefumigation darkness, soil-plant-water stress, and phenylmercuric acetate (PMA) to protect tomato plants from ozone injury. Leaves of plants so treated showed reduced injury (Fig. 1) which was accompanied by considerable reductions in stomatal aperture. Similar results were obtained in bean plants pretreated with abscisic acid (24). While it is possible that these environmental and chemical factors prevented injury by different physiological mechanisms, these studies suggest stomatal closure, or more appropriately stomatal width reduction, as a significant mechanism of protection.

The protection aspect of plants from air pollution injury, overall, is best achieved by the development of cultivars fairly tolerant of, or resistant to pollutants, through systematic breeding programs. Breeding programs such as that of Engle and Gabelman (20) are a case in point. However, in the Gentile et al. study of tomato (27), the disease resistant accession *Lycopersicon pimpinellifolium* had the greatest sensitivity to ozone; in contrast 'Manapal' combines both leaf mold-resistance with ozone tolerance.

In regard to short-term solutions, many of the atmospheric environmental factors do not lend themselves to manipulation. Hence, not much can be done with them to protect plants from air pollution damage in the field. However, knowledge of the activities of some of these factors is crucial in the manipulation or utilization of other factors of protection. In greenhouse crop production, environmental factors bear more relevance to the protection aspect since such factors as temperature, light, and humidity may be controlled to minimize air pollution damage. But even in this case, the simple provision of filters provides ample protection for greenhouse-grown plants. The use of chemicals is feasible and should be further explored. Application of chemicals such as antioxidants and vitamins is economically infeasible and has therefore not been commercially adopted. This stems not only from the high cost of the chemicals, but also from the need for repeated applications for effectiveness. However, the use of certain fungicides and growth regulating chemicals which are already routinely utilized in the horticultural industry is practicable since they confer multiple benefits. More studies of such agricultural chemicals will be of benefit in terms of the protection of horticultural plants from air pollution damage.

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