Studies on inter-relationship between air quality and agricultural plant ecosystem are necessary in order to improve the yield of agricultural crops, as suggested by Heck (1982), mainly because the phytotoxic air pollutants, alone or in mixtures, are responsible for substantial yield losses in several crops. Air pollutants are now of great concern to agricultural scientists, because they injure plant foliage, significantly alter their growth and yield and change the quality of the marketable plant products. The air pollutants are also supposed to increase or decrease the plant diseases caused by biotic plant pathogens (Heagle, 1973).

Air pollution is a source-transport-effect phenomenon and as such is analogous in many ways to the plant disease. To obtain a clear understanding of how air pollutants affect plants, it is important to know what are compounds that damage plants and where and how they originate. Broadly the air pollutants are of two types (Wood, 1968):

1. Primary pollutants
2. Secondary pollutants

Primary pollutants are those that originate at the source in a form toxic to plants, e.g. \( \text{SO}_2 \), HF, \( \text{NH}_3 \), CO,
Secondary pollutants are the result of reactions between pollutants originating from the source and other atmospheric factors e.g. PAN, \( O_3 \), acid rain. On the basis of their physical appearance, the air pollutants can also be grouped into two categories - gaseous and particulate air pollutants. The most common gaseous air pollutants injurious to plants are \( O_3 \), PAN, \( \text{SO}_2 \), \( \text{Cl}_2 \), \( \text{C}_2\text{H}_6 \), \( \text{HF} \), \( \text{H}_2\text{S} \), \( \text{NOx} \), etc. and the major particulate air pollutants include coal dust, flyash, cement dust, soil dust particles etc. Some primary air pollutants like \( \text{NOx} \), \( \text{SO}_2 \) released into the atmosphere, when come in contact with the water and atmospheric precipitation are converted into the acids and fall down. This condition of environmental pollution is called 'Acid rain' (Likens and Bormann, 1974). According to Das (1986) acid rain is the most acute and severe problem in developed countries, while in the developing countries acid rain problem is not so serious. The particulate air pollutants are the major problem in developing countries. In India, 40-44% of air pollutants are particulate matters and these are extremely troublesome, posing a great threat to plants and other living beings (Das, 1986).

**AIR POLLUTION EFFECTS ON PLANTS**

Study of plant diseases caused by air pollution began in the 19th century (Heagle, 1973). As the pathogenic diseases, the extent and nature of injury or damage caused by air pollutants is determined by genetic and environmental
factors of plant as well as by level and duration of exposure to pollutants, the terms injury and damage are often used interchangeably (Guderian et al., 1960). The designation pathogen is given to the living inducers of diseases by many pathologists. But diseases induced by abiotic factors e.g. air pollutants, drought, extremes of temperature etc. have many features in common with those induced by biotic pathogens. For this reason, Cowling and Horsfall (1979) preferred to use term 'pathogen' to denote any inducer of disease. Several workers have reported the effects of different air pollutants on the plants. These pollutants affect physiology and biochemistry of plants resulting in the visible symptoms like chlorosis, necrosis, early senescence, stunting and several other symptoms depending upon the types of air pollutant involved (Darley and Middleton, 1966; Brandt and Heck, 1968; Barret and Benedict, 1970). The plant sensitivity and resistance to air pollutants is altered when the concentration and duration of exposure exceed the plant's genetic capability to withstand the stress (Reinert et al., 1982).

GASEOUS AIR POLLUTANTS (PRIMARY TYPE)

Sulphur dioxide (SO₂)

Sulphur dioxide, a pollutant known for more than 100 years to be toxic to plants is emitted from the combustion of coal, production, refining and utilization of petroleum and natural gas, manufacturing and industrial utiliza-
tion of sulphuric acid and sulphur and the smelting and refining of ores, especially of copper, lead, zinc and nickel. The combustion of coal represents the major source of \( \text{SO}_2 \) and the amount of \( \text{SO}_2 \) emitted depends upon sulphur content of the coal, among the other things. The sulphur content of the coal varies from 1% to 6% of the total weight. The coal burning power plants represent the most important single source of \( \text{SO}_2 \) (Wood, 1968). The concentration of sulphur dioxide at ground level depends upon the amount and concentration(s) of emission, distance from the source and meteorological and topographical conditions. In general, \( \text{SO}_2 \) concentration decreases rapidly with distance from the source and with increased air movement. \( \text{SO}_2 \) concentration near point sources, such as coal burning power plants and smelters, with little or no pollution control equipment, may be high as 1-3 ppm. In large urban areas \( \text{SO}_2 \) concentration may range from 0.05-0.40 ppm (Heagle, 1973).

In general, \( \text{SO}_2 \) causes several types of symptoms on plants and plant parts. It enters through the stomata in the mesophyll tissue of the leaves and reacts with water to produce sulphite ion which is slowly oxidized to sulphate ion. The sulphate ion may then be utilized by the plant as nutritional sulphur and converted to organic form (Thomas et al., 1944). The sulphite and sulphate ions are toxic to plant cells when present in excessive amounts. The sulphite ions are, however, about 30 times more toxic than the
sulphate ions (Thomas et al., 1943). Due to the SO$_2$, two general types of markings designated as chronic markings and acute markings, appear depending upon the accumulation of sulphite ions. The chronic type markings are general chlorotic appearance of the leaf, mild chlorosis, yellowing of leaf and silvering or bronzing of the under surface. In some plants white type of chronic markings and appearance of red, brown or black coloured patches on the leaves are seen (Barret and Benedict, 1970). Acute injury resulting from the absorption of lethal quantities of SO$_2$ appears as marginal or intercostal areas of dead tissue. These areas at first show a grayish-green water-soaked appearance but on drying become bleached ivory in colour. After a period of time, the dead or necrotic areas may fall out leaving a very ragged appearance on the leaf. When the major portion of the leaf is so injured, an abscission layer is often formed at the base of the petiole and the leaf is shed (Barrett and Benedict, 1970). At low concentration, it causes chlorosis of leaves without formation of necrotic lesions and the veins characteristically remains green (Darley and Middleton, 1966; Agrios, 1978).

As SO$_2$ enters through stomata, factors that affect stomatal opening influence the response to plants to SO$_2$ (Thomas, 1951, 1961; Negherborn, 1966; Daines, 1968). Resistance of plants to SO$_2$ is also governed by soil moisture (Zimmerman and Crocker, 1934). When the leaves are turgid,
they are more sensitive to SO$_2$ than the wilted, since wilted plants are likely to have closed stomata. Thus, soil moisture stress greatly reduces the sensitivity of plants to SO$_2$. Atmospheric humidity is also an important factor related to SO$_2$ sensitivity of plants because it regulates stomatal opening (Thomas et al., 1943). With high humidity, plants show greater SO$_2$ sensitivity. Low concentrations of SO$_2$ also injure epidermal and guard cells leading to increased stomatal conductance and greater entry of SO$_2$ in plants (Black and Unsworth, 1980). In some plants stomatal conductance is, however, reduced during SO$_2$ exposure and this reduction might be one mechanism of resistance (Kobriger et al., 1984; Winner and Monney 1980; Bonte et al., 1977). The stomatal closure may be related with high SO$_2$ concentrations and opening to low concentrations (Unsworth and Black, 1981). Generally, SO$_2$ reduces net photosynthesis in all plants at all concentrations but dark respiration and transpiration are increased. Short and long term exposures have similar effects in this respect (Black and Unsworth, 1979; Mc Laughlin, et al., 1979; Takemoto and Noble, 1982; Saxe, 1983a). Plants generally show rapid recovery of these processes after termination of exposure lasting upto several days.

The effects of SO$_2$ on the enzyme systems and metabolic processes have been studied by several workers who observed changes in the activities of many enzymes. These changes are affected by SO$_2$ concentration, plant species, plant
age and environment. In some cases, enzyme activity is increased by exposure of the plants to low levels of SO₂ and decreased by higher concentrations (Horsman and Wellburn, 1977; Soldatini and Ziegler, 1979; Wyss and Brunold, 1980; Pierre and Queiroz, 1982; Tanaka et al., 1982). Plant metabolism is affected by SO₂ in a variety of ways. SO₂ stimulates phosphorus metabolism (Plesnicar, 1983) and reduces foliar chlorophyll concentration (Pandey and Rao, 1978; Lauenroth and Dodd, 1981). Carbohydrate levels are increased by low concentration of SO₂ and decreased by higher concentrations (Kozoiil and Jordon, 1978). In soybean when exposed to SO₂ significant reduction in yield was found due to loss in both seed weight and number of seeds produced by the plants, while seed quality was less affected. Although at higher exposure levels protein contents decreased slightly and concentrations of some mineral elements were altered (Sprugel et al., 1980).

SO₂ altering the physiology and biochemistry of plants affects their growth, development and productivity significantly. The effects of SO₂ in both glasshouse and ambient air on the plants like wheat, soybeans, groundnut, maize, alfalfa, tomato, snap-bean, tobacco, cucumber etc. have been studied by several workers (Laurence, 1970; Lockyer and Cowling, 1981; Lotstein et al., 1983; Mishra, 1980; Mejstrick, 1980; Pandey and Rao, 1978; Saxe, 1983b, Sprugel et al., 1980).
Oxides of Nitrogen (NOx)

Nitric oxide (NO) and nitrogen dioxide (NO\textsubscript{2}) are the two significant gases in the nitrogen oxide group of air pollutants which are produced primarily by high-temperature combustion (Taylor and MacLean, 1970). Nitrogen oxides are produced from the oxygen and nitrogen in the air by hot combustion sources, such as open fires, furnaces and automobile combustion chambers. Combustion of petroleum products are the major source of NO\textsubscript{x}. In this process nitric oxide is oxidised to nitrogen dioxide (Benedict and Breen, 1955; Agrios, 1978). Nitrogen dioxide in concentrations of 2-3 ppm causes bleaching of plants similar to that caused by SO\textsubscript{2} and it also produces necrotic lesions and excessive defoliation (MacLean et al., 1968; Agrios, 1978). There is no report of visible symptoms of leaf injury from nitric oxide (Taylor and MacLean, 1970). Acute foliar markings produced by high concentration of NO\textsubscript{2} exposure are characterised by water-soaked lesions, which first appear on the upper leaf surface followed by rapid tissue collapse. The lesions with time extend throughout the leaf and produce small irregular necrotic patches. The necrotic patches are usually white to tan or brown but sometime bronze in colour. The interveinal lesions are prominent at the apex and along with margins, but may occur on the leaf surface (Benedict and Breen, 1955; Middleton et al., 1958; Taylor and Eaton, 1966, MacLean et al., 1968). In chessecweed, Kentucky bluegrass and mustard, NO\textsubscript{2} exposure
resulted in a polished, dark waxy coating on the leaf surface which persisted for about 1 week after exposure while in sugarbeet, NO₂ developed grey glazed appearance on the leaves (Czech and Nothdurft, 1952; Benedict and Breen, 1955). MacLean et al. (1968) observed that besides the foliar symptoms, high concentration of NO₂ causes abscission of leaves and fruits of citrus and defoliation of azalea and hibiscus. NO₂ uptake is decreased with the increase in soil salinity which is associated with reduced stomatal conductance. Such impact of NO₂ treatment of beans was observed by Fuhrer and Erismann (1980).

Although the NO₂ concentration and duration of exposure are both important factors to be considered in determining the expected severity of injury to plants in the case of high concentration exposures, there is no direct relationship between time and concentration, except within very narrow ranges. The concentration of NO₂ influences the extent of injury more than the duration of exposure (MacLean et al., 1968). In the ambient condition, NO₂ affects plant growth even at the concentrations less than 1 ppm (Taylor and Eaton, 1966).

GASEOUS AIR POLLUTANTS (SECONDARY TYPE)

Ozone (O₃)

Ozone is the most important plant pathogenic component of photochemical oxidant air pollution. Exhau...
biles and other internal combustion engines are probably the most important sources of ozone and other phytotoxic pollutants. Incompletely burned hydrocarbons and NO$_2$ are released into the atmosphere by the automobile exhaust. In the presence of UV light, this NO$_2$ reacts with oxygen and forms O$_3$ and NO. The ozone may react with NO to form the original compound. But in the presence of unburned hydrocarbons NO reacts with hydrocarbons instead of ozone and therefore, O$_3$ is released in the atmosphere (Agrios, 1978). The naturally produced O$_3$ concentration at ground level is generally less than 0.03 ppm.

Ozone enters through stomata in leaves, where it accumulates in the palisade layer ultimately causing bleaching or discolouration and collapse of the palisade cells. O$_3$ affects primarily expanding leaves, but not very young or old, mature leaves. O$_3$ causes tippling, mottling and chlorosis of the leaf, usually on the upper leaf surface. The colour of the affected leaves varies from light tan to red or almost black, depending upon the plant. Affected leaves of some plants such as citrus, grapes and pines drop prematurely (Darley and Middleton, 1966; Agrios, 1978). Plant response to O$_3$ is, however, dependent on various environmental factors (Heck, 1968; Ting and Dugger, 1968).

The most common symptom on many deciduous trees, shrubs and some herbaceous plants is localized thickening
and pigmentation of the cell walls resulting in sharply defined small dot-like coloured lesions (Ledbetter et al., 1959). Generally the interveinal region is injured, so lesions are usually angular in shape. The veins are usually not affected except in plants where pigment formation takes place. Pigment formation can produce an overall colouration of the upper leaf surface when the lesions are dense (Heck et al., 1970). Small unpigmented necrotic spots or more general upper surface bleaching is a common type of injury on most of herbaceous and many woody plants (Ledbetter et al., 1959). When the injury becomes more severe then upper epidermal cells collapse and become colourless. A shiny oily or waxy appearance of the upper leaf develops in some plants during O₃ exposure. These symptoms disappear after the termination of the exposure. A water-soaked appearance often develops followed by drying and bleaching which results in typical bifacial necrosis within one or two days (Heck et al., 1970). Epidermal cells remain uninjured while the palisade cells and spongy mesophyll become injured. Many injured cells remain alive but chloroplast is disrupted and the chlorophyll amount is reduced significantly (Hill et al., 1961). Chlorotic mottling or chlorotic flecks are common symptoms on pine. Alfalfa develop large light green chlorotic areas with many irregular islands of normal green tissue dispersed in them. In some plants the tissue eventually becomes uniformly chlorotic and leaves may drop prematurely (Ledbetter et al., 1959).
The entrance of O$_3$ into plant leaves through stomata is well established. It has been observed that resistant bean cultivar have fewer stomata than a sensitive (susceptible) cultivar. During the exposure, stomata on the resistant cultivar showed partial closure, whereas those on the sensitive cultivar did not show any closure (Butler and Tibbitts, 1979). Stomatal closure caused by moisture stress or other factors can protect even the sensitive species from injury (Macdowall, 1965). There are some evidences that O$_3$ itself may induce stomatal closure, thus reducing the amount of O$_3$ entering the leaf and contributing to the resistance to O$_3$ injury in some plants (Engle and Gabelman, 1966). Stomatal closure was more important than stomatal number in determining sensitivity. Bean plant showed stomatal closure even at low concentration (Heck et al., 1986). However, no relationship was found between O$_3$ sensitivity and the number of stomata or the rate of gas exchange in azalea, sweet corn, soybean and tobacco (Gesalman and Davis, 1978; Harris and Heath, 1981; Heck et al., 1986). In the controlled exposure conditions, the impact of O$_3$ on the several physiological activities like photosynthesis, respiration, transpiration and the accumulation of starch, sugar, mineral etc. has been studied by several workers on different crop plants (Blum et al., 1982; Hill and Littlefield, 1969; Jensen, 1981; Macdowall, 1965; Pell and Brennan, 1973; Todd, 1958; Todd and Probst, 1963).

Ozone is reported to cause various types of damages
in a number of crops like tomato, potato, cotton, pepper, sunflower, soybean, snapbean, clover etc. 0.04-0.10 ppm concentration of O$_3$ for 8 h is sufficient to produce visible foliar injury in sensitive plants while 0.08-0.20 ppm O$_3$ for 8 h would be required to produce injuries in resistant plants (Heagle, 1973). Ozone in ambient conditions has been found to cause reduction in the tomato yield and was responsible for 85% of reduced fruit size along the gradient at the 0.10 ppm concentration for 20 h, 50% reduction in yield has been recorded (Oshima et al., 1977a, 1977b). In the controlled exposure studies on several crop plants like tomato, potato, pepper, carrot, cotton, soybean, snapbeans, clover, fescue etc., the impact of different concentrations of O$_3$ has been determined by various workers (Bennett et al., 1979 Bennett and Oshima, 1976; Blum and Heck, 1980; Blum et al., 1983a, 1983b; Clarke et al. 1983; Grunwald and Endress, 1984; Henderson and Reinert, 1979; Letchworth and Blum, 1977; Manning and Feder, 1976; Oshima et al., 1979; Pell et al., 1980; Shimizu et al., 1981).

**Particulate air pollutants**

A major part of air pollutants are particulate matters. The major particulate air pollutants are coal dust, flyash, lime dust, cement dust, soil dust particles, etc. Important sources of particulates are production of coal and cement; combustion of coal, gasoline and fuel oil, lime kiln operations, incineration and soil erosion, agricultural burning
and wrong agricultural practices, volcanic eruptions, transportation and construction etc. According to Das (1986), in the developing countries particulate air pollutants are the major problem, while in the developed countries the problem of particulate air pollutants is not so important. In India, 40-44% air pollutants are of particulate type.

Particulate matters settle on plant parts and cause severe damage to the plants. They cause chlorosis, necrosis, and death of the tissue, when the heavy deposition of the particles occurs. Many particles are byproducts of agricultural practices and are usually inert (Darley and Middleton, 1966; Heck et al., 1970). Cement dust, alkaline in nature produces injury to plants in the close vicinity (Darley, 1966). In a closed chamber study, wheat plants showed reduction in transpiration rate, chlorophyll content and productivity due to cement dust pollution (Singh and Rao, 1981). Lime dust particles form encrustations on leaves of vegetation with a resultant reduction in photosynthesis, vigour and hardiness of the plants. Heck et al., (1970) noticed that high particulate emission from the different sources caused the reduction in quality of the vegetables and fruits growing close to the source.

Colwill et al., (1979) observed dust deposits on the leaves of the plants grown along the road side with highly busy traffic. Such plants showed poor growth. There have been numerous reports that dust of varying origins
interfere with stomatal functioning mostly by filling and blocking the stomatal aperture (Ricks and Williams, 1974; Flückiger et al., 1978, 1979), increase leaf temperature (Eller, 1977; Flückiger et al., 1978) and transpiration (Beasley, 1942; Eveling, 1969), reduce photosynthesis (Darley, 1966), and increase the uptake of gaseous air pollutants (Ricks and Williams, 1974). All these effects eventually result in poor growth of suffering plants.

Acid rain

Some NO\textsubscript{x} primary air pollutants (SO\textsubscript{2} and NO\textsubscript{x}) are converted into acids after contact with water present in atmosphere and with atmospheric precipitation come down. This is referred to as acid rain. According to Cowling (1982) the phenomenon of rain fall acidification by pollutant emissions was recognized by Hales as early as 1757 in England and its effects were first examined by Robert Angus Smith as early as 1870s. However, modern attention to acid rain began in 1948 (Oden 1968).

Acid rain of pH 3.0-3.6 are reported from Sweden, Norway and eastern United States. The average acidity of rainfall in eastern United States was estimated to be below pH 4.5 in 1972-73. The changes have been attributed to acidic substances formed in the atmosphere, mainly from oxides of sulphur and nitrogen produced during combustion of fossil fuels (Cogbill and Likens, 1974; Likens and Bormann, 1974).
Acid rain causes primarily the acidification and alteration of water and soil. It has been recognized that herbaceous plants are more sensitive to direct injury by acid rain than woody plants (Heck et al., 1986). The most striking effect on vegetation was reported on peat moss (Sphagnum), an aquatic plant. Lakes were found to be acidified at the bottom up to 18 meter depth in Sweden (Grahn et al., 1974). Direct injury of terrestrial plants by artificial mists of simulated rain containing dilute sulphuric acid, increased leaching of nutrients from pinto bean and sugar maple seedling foliage (Wood and Bormann, 1974). In soybean and kidney bean plants when exposed to acid rain of pH 3.2 and pH 6.0 for 17 weeks duration, intermittently in the field condition, no important effects were detected in number of pods formed, in soil acidity or in amounts of essential elements in the soil or foliage of the plants. No significant difference were observed in fresh weight of shoots, roots or pods both in field and glasshouse (Shriner and Johnston, 1981).

Pollutant Mixture

Pollutant mixture effects to plants were recognized in 1970s. The studies have generally shown increased effects with mixtures of pollutants over effects from individual pollutants. However, the combined effects of air pollutant mixture can be either synergistic, antagonistic or additive. Responses of plants to pollutant mixtures include visible
symptoms of injury, altered growth and development, physiological and metabolic imbalances, and the accumulation of certain elements and metabolites. Decrease in plant growth and yield are often the critical agricultural responses. The most important pollutant mixtures are $O_3 + SO_2$, $SO_2 + NO_2$ and $O_3 + SO_2 + NO_2$. Several other pollutant mixtures like $O_3 + NO_2$, $SO_2 + Hg$, $SO_2 + NaF$, $NO_2 + HF$, $O_3 + H_2S$ and $O_3 +$ acid rain are also known to cause injury in several plants (Reinert, 1984; Heck et al., 1986).

$O_3 - SO_2$ mixture showed synergistic, antagonistic and additive interaction in the different concentrations on several crop plants (Shew et al., 1982; Ormrod et al., 1983; Shertz et al., 1980; Foster et al., 1983; Heagle and Johnston, 1979; Pratt et al., 1983). But in a study Olszyk and Tibbits (1982) recorded that the foliar injury, reduced leaf area, chlorophyll, leaf weight, did not show any interactive response when garden pea were exposed to 0.06 and 0.27 ppm $O_3$, 0.11 and 1.72 ppm $SO_2$ mixture for 2, 4 or 8 h.

ROOT NODULE BACTERIA

Root nodule bacteria fix symbiotically the atmospheric nitrogen in association with leguminous plants. The nodule-forming bacteria belong to Rhizobium and Bradyrhizobium of the family Rhizobiaceae. Genus Rhizobium includes fast growing bacteria while the slow growing bacteria are included in Bradyrhizobium. (Jordan, 1982; Huang, 1987). Rhizobium
and *Bradyrhizobium* are gram negative bacteria, rod-shaped of short to medium size. Usually nodule-forming bacteria live freely in soil and in the root region of both leguminous and non-leguminous plants. However, they can enter into symbiosis only with leguminous plants, by infecting their roots and forming nodules on them. Different species of *Rhizobium* respond to the different plants. In legume-root-nodule symbiosis, root nodule bacterium is recognized as microsymbiont. When nodule becomes senescent after a period in nitrogen fixation, decay of tissue sets-in liberating motile forms of root nodule bacteria into soil which normally serve as a source of inoculum for the succeeding crop of a given species of legume (SubbaRao, 1972, 1975). Root nodule bacteria penetrate in the root from the root hair through the intercellular spaces and form nodule in the upper cortical regions. The core of a mature nodule constitutes the bacteroid zone surrounded by several layers of cortical cells. The volume of bacteroid zone in effective nodules has a direct positive relationship with the nitrogen fixed. The effective nodules are generally large and pink in colour due to leghaemoglobin (Bergerson and Briggs, 1958).

**ROOT-KNOT NEMATODES**

Root-knot nematodes (*Meloidogyne* species), a highly destructive group of plant parasitic nematodes, are worldwide in distribution. They have extensive host range and interact with a large number of fungi, bacteria and viruses.
In the areas where the root-knot nematodes are not managed, average crop yield losses are estimated to be about 25% with damage in individual fields ranging as high as 60% (Sasser, 1980; Sasser and Carter, 1982). Out of more than 70 species of Meloidogyne known at present, 4 species viz., Meloidogyne incognita, Meloidogyne javanica, Meloidogyne arenaria, Meloidogyne hapla are recognized as most common and damaging throughout the world and are called major species of root-knot nematodes (Taylor et al., 1982). These species cause root-knot disease in many different kinds of crops like cereals, vegetables, pulses, fibre-yielding crops, fruit crops, plantation crops, ornamentals etc. (Sasser, 1980; Sasser and Carter, 1982). Root-knot nematodes also interact with other plant pathogenic organisms synergistically causing more loss to the plants. Most frequent interaction of root-knot nematode has been reported with fungi and bacteria (Powell 1971a, 1971b; Taylor, 1979; Khan, 1984; Sikora and Carter, 1987).

**INTERACTION OF NODULE-FORMING BACTERIA AND PLANT PARASITIC NEMATODES**

Root nodule bacteria are found in the nodules on the root surface of legumes while the plant parasitic nematodes have the different feeding sites depending upon the mode of parasitism. Some nematodes are surface feeder while others are endoparasitic. So, these nematodes interact with
Rhizobium in different patterns. Interactions of Rhizobium spp. with sedentary endoparasites like Heterodera glycines and Meloidogyne spp. have been demonstrated on some crops. It has been observed that soybeans infected with H. glycines usually have few bacterial nodules (Barker et al., 1972; Hussey and Barker, 1976). However, on clover Heterodera trifolii and M. javanica were not found to have much effect on nodules. Both nematodes reproduced well in nodules. However, nodules containing M. javanica deteriorated more rapidly than non-infected, reducing the total benefit from the nitrogen-fixing bacteria (Taha and Raski, 1969). The formation of nodules on root-galls and gall formation on the nodules have been reported by Robinson (1961) and Taha and Raski (1969). Ayala (1962) reported parasitism of bacterial nodules by Rotylenchulus reniformis in Cajanus indicus. Nigh (1966) observed the reduction in nodulation of alfalfa by M. javanica. Reduced nodulation due to root-knot nematode infection observed in soybean was because of the possibility that nematodes rendered the infected plant roots physiologically incompatible to the bacteria (Balasubramanian, 1971). Cyst nematodes, Heterodera spp. inhibit nodulation and N-fixation in most of the plants. A drastic reduction of total nitrogen in H. trifolii infected plants caused their stunting. H. trifolii reproduced readily in white clover while the nodule number was altered by root suppression (Taha and Raski, 1969). Different races of H. glycines show different effects on root nodulation and N-fixing capa-
city of soybean. Race 1 was found more effective than race 2 and 4. In race 1, nodulation and N-fixation increased initially but afterward decreased (Lehman et al., 1971). Barker and Huising (1970) also reported the antagonistic interaction between H. glycines and R. japonicum. Barker et al. (1971) found that R. japonicum nodular tissue was unfavourable for cyst development of race 1 of H. glycines. H. glycines also inhibits leghamoglobin content in soybean (Huang and Barker, 1983). Sharma and Sethi (1975) also reported that nematodes interfered with the leghemoglobin content of the cowpea root nodules, with M. incognita causing more reduction than H. cajani. Bopaiah et al. (1976) observed a reduced nodulation and less nitrogen content in mung (Vigna radiata) when M. javanica preceded Rhizobium. Xylary elements in soybean and peanut serve as barrier to the penetration of migratory endoparasite like Pratylenchus penetrans and octoparasite like Belonolaimus longicaudatus but sometimes these nematodes caused the deterioration of bacteroids present in the nodules of the Wando pea plants lacking xylary elements (Barker and Hussey, 1976).

INTERACTION OF AIR POLLUTANTS AND ROOT NODULE BACTERIA

On this aspect little attention has been given thus far. But in the studies carried out, it has been found that generally all the pollutants have negative effect over the root nodule bacteria. Reiner and Weber (1980) have found that O_3 reduced the number and dry weight of the bacterial
nODULES IN SOYBEAN. Blum and Tingey (1977) have also reported that acute O₃ exposure inhibited bacterial nodules in soybeans. SO₂ and NO₂ alone and in mixture also significantly reduced nodule number but no significant effect was observed on the individual nodule size. This reduction in nodule number resulted in the reduction of N-fixation in soybean (Klarer et al., 1984).

The simulated acid rain of pH 3.2 also inhibited bacterial nodulation in soybeans and kidney beans. The total nodule weight was also reduced, no significant differences were detected in average weight of individual nodules, which indicate that simulated acid rain appeared to have effect on nodule formation than the development of nodules which have once initiated. It is also reported that nodulation was lesser in the plants, when acidified rain treatment was given on foliage only, compared with the plants having rain on both foliage and soil (Shriner and Johnston, 1981). The nodulation in soybeans and kidney beans has also been found to be inhibited by simulated acid rain of pH 3.2 by Waldron (1978). He also found that hydrogen ions causes all these changes in nodulation rather than sulfate ions and suggested it a host mediated effect.

INTERACTION OF AIR POLLUTANTS AND PLANT PARASITIC NEMATODES

The effect of air pollutants on the host-nematode relationships has not yet been studied extensively. But
there are a few reports. Bassus (1968) observed that the saprophagous and predaceous nematode populations were more in the forest areas, severely damaged by SO\textsubscript{2} and alkaline particulated material than the slightly damaged areas. Weber \textit{et al.}, (1979) studied the response of plant parasitic nematodes to O\textsubscript{3} and SO\textsubscript{2}, singly and in mixture. Selecting five plant parasitic nematode species with different modes of parasitism, they exposed begonia and soybean plants infected with the nematodes to SO\textsubscript{2} singly or in combination, and to charcoal filtered control air and found different responses of the nematodes to air pollutants. Exposure of infected soybean plants to O\textsubscript{3} and O\textsubscript{3}-SO\textsubscript{2} mixture, inhibited reproduction and development of \textit{Heterodera glycines} (sedentary endoparasite) and \textit{Paratrichodorus minor} (ectoparasite) but the increase of \textit{Belonolaimus longicaudatus} was unaffected. Exposure of soybean plants to SO\textsubscript{2} enhanced the reproduction of \textit{Pratylenchus penetrans} (migratory endoparasite) compared with that in plants exposed to the charcoal filtered control air or O\textsubscript{3}. Foliar injury of begonia by O\textsubscript{3} or O\textsubscript{3}-SO\textsubscript{2} mixture inhibited \textit{Aphelenchoides fragariae} (foliar migratory endoparasite). Suppressive effects on \textit{A. fragariae} were greater in leaves pre-xposed to O\textsubscript{3} or O\textsubscript{3}-SO\textsubscript{2} mixture rather than after leaves were inoculated with the nematode.

Shew \textit{et al.} (1982) studied the response of tomato to possible interactions between O\textsubscript{3} and nematode (\textit{Pratylenchus penetrans}) inoculations and found that the presence
of *P. penetrans* attacking the roots enhanced the negative effects of \( \text{O}_3 - \text{SO}_2 \) on leaf growth but suppressed the inhibitor effects of \( \text{O}_3 - \text{SO}_2 \) mixture on axillary shoot growth. In the ambient ozone exposure, 20% more galls developed on tobacco plants inoculated with root-knot nematode, *Meloidogyne hapla* when compared with plants sprayed with antioxidant. Increase in dry weight of shoot, root and biomass of plants sprayed with antioxidant was also observed. These results indicated that antioxidant indirectly reduced gall development. Thus the tobacco plants infected with *M. hapla* were found more susceptible to ambient \( \text{O}_3 \) (*Bisessar and Palmer, 1984*). Shriner (1978), however, recorded decrease in root infection and reproduction of *M. hapla* infecting red kidney beans in field conditions, treated three times weekly with simulated acid rain at pH 6.0 or 3.2.

In a recent study by Bolla and Fitzsimmons (1988), white, Scots and Austrian pine seedlings were treated with simulated acid rain (pH 3.6) and inoculated with specific pathotype of *Bursaphelenchus xylophilus*. Oleoresin concentration increased slightly and carbohydrate concentration decreased in acid rain treated seedlings. These changes were significant in the white and Scots pine seedlings, when nematode inoculation followed the acid rain treatment. Wilting of seedlings was delayed and nematode reproduction decreased in acid rain treated white pine seedlings inoculated with *B. xylophilus*. Acid rain treated Austrian pine seedlings were resistant to *B. xylophilus*, but acid rain treated
Scots pine seedlings lost tolerance to \textit{B. xylophilus} and wilted 50-60 days after inoculation.

**INTERACTION OF AIR POLLUTANTS AND OTHER PLANT PATHOGENS**

The interaction of air pollutants with several plant pathogens other than plant parasitic nematodes have been recognised and reviewed by several workers (Bruck and Shafer, 1984; Darley and Middleton, 1966; Heagle, 1973; 1982; Heck et al., 1986; Treshow, 1975). These plant pathogens are fungi, bacteria and viruses.

**Interaction of Air Pollutants and Fungal Plant Pathogens**

Investigations have been carried out on the interaction of plant parasitic fungi and air pollutants both in ambient and in glasshouse conditions. The major air pollutants known to affect the host parasite relationship of plants infected with fungi are \( \text{SO}_2 \), \( \text{O}_3 \), \( \text{HF} \) and acid rain.

\( \text{SO}_2 \) usually inhibits the growth and development of plant parasitic fungi in the polluted area (Scheffer and Hedgcock, 1955; Skye, 1968). In some studies, it has been shown that with the increasing distance the effect of \( \text{SO}_2 \) on disease incidence and development decreases notably (Linzon, 1958). Field observations have indicated that the obligate parasitic fungi are generally more sensitive to \( \text{SO}_2 \) than non-obligate parasitic fungi. This has been substantiated by the results of glasshouse studies in controlled
conditions (Weinstein et al., 1975). SO₂ was found to inhibit parasitism of wheat by *Puccinia graminis*, but type of wheat resistance to rust was critical in response depending upon different cultivars (Laurence et al., 1979). Non-obligate parasitic fungi are inhibited, stimulated or do not respond to SO₂ pollution. Exposures to SO₂ decreased parasitism of bean by *Uromyces phaseoli* but did not affect parasitism of tomato leaves by *Alternaria solani* (Weinstein et al., 1975). The number of lesions caused by *Helminthosporium maydis* was found to decrease by 38% when exposed to SO₂ on 8 days before inoculation (0.15 ppm for 14 h/day). If the exposures occurred on the 8 days before and on the 2 days after inoculations the number of lesions decreased by 13-16% only (Laurence et al., 1979).

Weidensaul and Darling (1979) recorded increase in the number of lesions caused by *Schirrhia acicola* on needles of Scots pine seedling, when exposed to 0.20 ppm for 6 h of SO₂ for 5 days. Fungal growth and spore germination were also affected by SO₂. Within the plant tissues, the fungal hyphae showed resistance to SO₂. The hypha of different fungi showed variations in sensitivity to SO₂ doses (Mc Callen and Weedon, 1940). *Botrytis* sp. (cinerea type) in pure culture was resistant to 4.0 ppm concentration of SO₂ for 11 h, while *S. acicola* grew normally and produced viable conidia after exposure to 1.0 ppm SO₂ for 4 h (Ham, 1971). Saunders (1966) found that *Aspergillus niger*, *Alternaria*
brassicicola and Didymellina macrospora were unaffected in nutrient solution containing 90 ppm equivalent SO₂ while Penicillium was slightly stimulated in growth. The spores of most of fungi show great resistance to direct exposure to SO₂, even at the high doses (Couey and Uota, 1961; Hibben, 1966). Spore germination was inhibited more with increasing water content, in most of the fungi (Couey, 1965; Couey and Uota, 1961). Sharp (1967), however, reported that uredospores of Puccinia striiformis showed no resistance to SO₂ exposure.

O₃ inhibits obligate fungus parasitism, whereas facultative parasitism might be increased, inhibited or not affected. O₃ affects rust indirectly while powdery mildews seemed to be affected directly at the time of conidial formation, conidial germination and penetration. The mature spores showed resistance to ambient O₃ pollution (Heagle, 1973). Uromyces phaseoli, an obligate parasite on bean, has been reported to have both negative and positive response for O₃ in the controlled conditions (Resh and Runeckles, 1973). Microsphaera alni was found to be very resistant by Hibben and Taylor (1975) when exposed to 1.0 or 0.25 ppm of O₃ for 6 and 72 h respectively. However, the powdery mildew of barley, Erysiphe graminis has been observed to be sensitive to O₃ during conidial development, germination and penetration (Heagle, 1973). Botrytis squamosa, a facultative fungus, developed two times more lesions on the onion plants, exposed to O₃ (Wukash and Hofstra, 1976, 1977). The response
of O\textsubscript{3} to \textit{Helminthosporium maydis} on maize leaves depends on the time of exposure in relation to the stage of fungus development as well as the concentration of O\textsubscript{3} (Heagle, 1977). James \textit{et al.}, (1980) claimed that \textit{Heterobasidion annosum} can cause the death of pine tree injured by O\textsubscript{3}. \textit{Puccinia coronata}, crown rust of oat was slightly injured by O\textsubscript{3} and the uredia were significantly smaller in size, when exposed to 0.10 ppm O\textsubscript{3} for 6 h 10 days after inoculation (Heagle, 1970). The small doses of O\textsubscript{3} was found to be inhibitory for sporulation of wheat stem rust, \textit{Puccinia graminis}. This decrease in sporulation was due to injury of host mesophyll cells and decreased hyphal growth (Heagle and Key, 1973).

Fungus colonies on culture media are not much affected by exposure to large doses of O\textsubscript{3} although small doses can inhibit the colony growth, suppress development of aerial hyphae and decrease sporulation (Ingram and Haines, 1949; Hibben and Stotzky, 1969). In most of the fungi, the dry spores are more resistant to O\textsubscript{3} than wet spores (Hibben and Stotzky, 1969).

Acid rain has been also recognised to affect the host-parasite relationship of several fungi. Simulated acid rain caused inhibition of \textit{Cronartium fusiforme} on the willow oak inoculated with aeciospores. The number of infections and telia were decreased when rain acidified to pH 3.2 with H\textsubscript{2}SO\textsubscript{4} acid was applied on each of 14 days before and after
inoculation (Heagle, 1982). The number of *Helminthosporium maydis* lesions on maize increased when conidia were incubated in water at pH 3.5 before inoculation and the leaves were subsequently treated with rain at pH 3.5 (Shriner, 1978).

In a survey of fungi in the cement dust polluted area, Rai and Pathak (1981) found that total number of fungi associated with potato leaves were more in polluted area which indicated that cement dust was not inhibitory to fungi. The maximum number of *Penicillium javanicum* isolates was found in cement dust polluted areas while *Alternaria solani* was less.

**Interaction of air Pollutants and Plant Pathogenic Bacteria**

The effects of different air pollutants on plant pathogenic bacteria have been recognized (Heagle, 1973, 1982; Laurence and Aluisio, 1981; Heck et al., 1986). SO$_2$ exposure is reported to reduce the rate of lesion development and lesion size on plants suffering with bacterial diseases. Exposure time and dosage of pollutants have been observed to be limiting factors (Laurence and Aluisio, 1981). *Corynebacterium nebraskense* was inhibited when maize plants were exposed continuously to SO$_2$ on 5 days before inoculation or 2 days after inoculation or in both. The inhibition was, however, maximum in the 2 days post-inoculation exposure. Similarly inhibition of *Xanthomonas paseoli* was found on soybean with exposure to SO$_2$. It was highest in both 5 days
pre- or post-inoculation exposures (Laurence and Aluisio, 1981).

Ozone is also known to inhibit the bacterial plant diseases, especially the bacteria causing foliar lesions. *Pseudomonas glycinea* infecting soybean leaves, when exposed to \( O_3 \) (0.08 or 0.25 ppm for 4 h) from 16 days to 1 h before inoculation or from 1 h to 1 day after inoculation, showed the decrease in number of lesions (Laurence and Wood, 1978a). Number of lesions on wild strawberry infected with *Xanthomonas fragariae* was decreased by \( O_3 \) (0.20 ppm for 4 h) (Laurence and Wood, 1978b). Simulated acid rain at pH 3.2 (0.63 cm over 10 minutes per day for 10 days) before inoculation is reported to increase the disease symptoms caused by *P. phaseolicola* on kidney bean. However, the symptoms were inhibited when the pH 3.2 rain treatments occurred on the 11 days after inoculation (Shriner, 1978).

Interaction of Air Pollutants with Plant Viruses

There have been few attempts to study the response of virus and virus infected plants to air pollutants. There are reports that \( SO_2 \) can increase viruses in plants of bean and maize irrespective of the duration of exposure. Southern bean mosaic virus and sulphur content in bean leaves were increased by continuous \( SO_2 \) (0.10 ppm for 7 days) exposure either before, after or both before and after inoculation. Increase in the severity of infection and symptoms, without
an increase in sulphur content, was observed for maize dwarf mosaic virus (MDMV) in plants exposed to $\text{SO}_2$ continuously before or after inoculation (Laurence et al., 1981).

Some workers have investigated the response of viruses to $\text{O}_3$ exposure. Davis and Smith (1974b) observed that pinto bean leaves were partly protected from $\text{O}_3$ (0.25 ppm for 4 h) when inoculated with bean common mosaic virus, 4, 5 or 6 days before exposure. The effect did not occur if plants were inoculated 3 days before exposure. Some viruses viz., tobacco ring spot, tomato ring spot, alfalfa mosaic and tobacco mosaic viruses also protected primary leaves of pinto beans from $\text{O}_3$, when inoculated 5 days before exposure (Davis and Smith, 1974a). There are also other reports which show that different viruses protected primary leaves of soybean, pinto bean etc. from injury caused by $\text{O}_3$ (Davis and Smith 1974a; Vargo et al., 1978). In field, tobacco infected with TMV exhibited 60% less injury from ambient $\text{O}_3$ (Bisessar and Temple, 1977). However, tobacco streak virus caused significantly more injury in tobacco exposed to 0.30 ppm of $\text{O}_3$ for 3 h on 1 or 2 days at 3 weeks after inoculation (Reinert and Gooding, 1978).

The mechanisms for virus induced changes in plants response to $\text{O}_3$ are unknown. Decreased stomatal conductance has been suggested as the mechanism for protection, but this was not proved in some plants. Virus titre, plant age and season have been recognized as important factors (Brennan
INTERACTIONS BETWEEN AIR POLLUTANTS, ROOT NODULE BACTERIA AND PLANT PARASITIC NEMATODES

The interaction between air pollutants, root nodule bacteria and plant parasitic nematodes has not gained much study. Weber et al. (1979) studied such interactions in a leguminous crop and recognized effects of interactions. During the study seven-day-old soybean seedlings were inoculated with *Rhizobium japonicum* and later after 15 days from sowing, the transplanted soybean plants were inoculated with four plant parasitic nematodes, i.e. *Heterodera glycines*, *Belonolaimus longicaudatus*, *Paratrichodorus minor* and *Pratylenchus penetrans* and exposed to $\text{SO}_2$, $\text{O}_3$, and $\text{O}_3+\text{SO}_2$ mixture. The effects of pollutant-nematode combinations on nodulation varied. Because of the severe inhibition of nodulation of soybean by *H. glycines*, the number of nodules from roots parasitized by this nematode did not differ among the pollutant treatments. In contrast, nodulation in plants parasitized by *B. longicaudatus* and *P. minor* was inhibited by exposure of soybean to $\text{O}_3$ and $\text{O}_3+\text{SO}_2$ mixture as compared to the control and $\text{SO}_2$ treated plants while *P. penetrans* and $\text{O}_3+\text{SO}_2$ mixture did not show any remarkable effect on nodulation. In this study $\text{O}_3$ and $\text{O}_3+\text{SO}_2$ mixture inhibited the growth of soybean both in the presence and absence of nematode and caused the injuries in leaves. $\text{SO}_2$ inhibited the growth of soybean inoculated with *P. penetrans* but did not
affect the penetration of *H. glycines* in soybean roots but inhibited the reproduction and development of *H. glycines* and *P. minor* while development of *B. longicaudatus* was unaffected. Exposure of soybean plant to *SO₂* enhanced the reproduction of *P. penetrans* compared with that in plants exposed to charcoal filtered air or to *O₃*. *O₃*-*SO₂* mixture also showed similar effects but not much significantly different from the control.

Air pollution effects on crop plants and plant diseases are new and developing areas of research and informations available are still meager. But whatever has been done on the above aspects, gives indication of air pollution damage to crops. Similarly, plant pathogens affecting crop plants are directly or indirectly affected, though informations on this aspect are rather negligible. Air pollutants affecting leguminous crops may imbalance their symbiotic relationship, the nitrogen transformation system, so beneficial for nitrogen economy of legume cultivations. Some studies as summarized above show the possibility of imbalances in this system. This needs to be further and thoroughly investigated and substantiated by more experimental data. Root-knot nematodes also impair nitrogen fixing capability of the system. At the same time, air pollution may stress the host-parasite relationships of root-knot nematodes. This has yet attracted very little attention of investigators. The impact of air pollution on this system and possibility
of synergistic or antagonistic relationship that may develop between various kinds of air pollutants and root-knot nematodes on crop plants are very little known and need to be substantially investigated. It may gradually add a new dimension to the field of Plant Nematology.