Effects of Acid Rain on Plant Growth and Development

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Abstract

Acid rain is a rain or any other form of precipitation that is unusually acidic and possesses elevated levels of hydrogen ions (low pH). Acid rain is caused by emissions of Sulfur dioxide and Nitrogen oxide, which react with the atomospheric water and water vapours to produce acids. Vegetation and soil are the prime receptor of acid deposition and function as sink. Monocotyledons are reported to be relatively less affected by acid rain as compared to dicotyledons and young rootlets, leaves and shoots are typically more sensitive to low pH conditions. It also affects the compositions/makeup of soil water which is the main medium of nutrient supply for the plants and soil microflora. Acidic rain solutions make their entry into the leaf tissue through the cuticle and produce marked effects on plants. Acid rain generally retards the growth of plants by stimulating abnormalities in metabolism of the plants, like photosynthesis, nitrogen and sulphur metabolism, however, there are exceptional cases of promoting growth as well. Present articles reviews studies conducted worldwide on the exposure of various crop plants to acid rain and its ultimate effects on plant growth and reproduction and draws attention for development of plant types suited to acid rain affected lands.

KEY WORDS: Acid rain, Air pollution, Development, Growth, Plants, Yield.

INTRODUCTION

Environment suffers many acute problems including pollution which is an undesirable change in the physical, chemical and biological characteristics of air, water and soil. Every nation on the globe is concerned about the increasing environmental pollution. Extremely rapid development of techniques and socio-economic changes on a world scale cause rapid environmental changes and increase in material needs. Modern social tendencies give preference to meeting the material and social needs of populations. Inhabitants in the vicinity of the industrial units suffer due to intolerable pollution from industrial discharges injurious to heath. The environment comprises material factors whose presence is decisive for survival and development of living organisms (oxygen, carbon, hydrogen, nitrogen), and factors regulating the life processes. Environment can also be polluted due to other reasons like application of new materials and plastics in building for the production of furniture, clothes, shoes, household and office equipments and calls for studies of their harmfulness for man allergies and poisonings etc.

Air pollution is indeed of major immediate global concern as whenever the balance of natural composition of air is disturbed, it has an adverse effect on environment and living beings. Air pollution is due to dust storms, marsh gas, respiration of organisms, decay and decomposition, forest fires, spores and pollen grains, mass consumption of air, reckless cutting of forests, green house effects, depletion of Ozone layer, population explosion, indiscriminate exploitation of natural resources, use of inorganic chemicals, insecticides, pesticides, generation of CO_2, SO_2, CO, chlorofluorocarbons (CFCs), Halons by industries, automobiles and refrigerations, solvents and foam blowing. Halons and CFCs are most dangerous and breaking ozone layer inviting ultraviolet rays which are damaging the genetic material (DNA) and are responsible for skin cancer. The new evidence is increasingly implicating it as a cause of the rarer but virulent cutaneous malignant melanomas. It impairs the body ability to fight it off and suppresses the efficiency of immune system, making it easier for tumours to take hold and spread. It also produces cataracts, eye disorders, damages crops, ecosystem and materials. Generally, air pollution is created by all over the earth crust by burning fossil fuels to run factories, machinery and all forms of transportation. This burning creates byproducts such as smoke and invisible irritants which contaminate our atmosphere. The discharge of industrial effluents, emissions and automobile gases exerts detrimental effects on natural ecology of life supporting systems, upon their release into natural air reservoir, water and soil. The toxic organic and inorganic pollutants present in automobile discharges affect the physiology and biochemistry of living organisms.

Man made air pollution in urban areas is often called as smog which has been observed over oceans, over the North Pole, and in their unlikely places. Increasing of CO_2 in the atmosphere, mainly due to the burning of fossil fuels, is causing a warming trend leading to climate change. The impact of such a change could be of sufficient magnitude to produce major physical, economical and social dislocations on a global scale. Main air pollutants are sulphur dioxide derived from coal and fuel oil used in the industry, particles (dust and soot from the industry) which represent nuclei for smoke formation in cities, and Carbon monoxide from motor vehicle exhausts which is toxic, causing headaches and even death at high concentrations. The other air pollutants include oxidants derived from motor vehicle exhaust and industry cause smog which irritates the eyes and reduces visibility, and Nitrogen oxides and lead added to motor fuel and expelled from exhaust which accumulate in the body. In general, all emission of smells and odours may cause discomfort and some are distinctly noxious to the health and general well being. The industrial sources of odours involve craft mills, oil refineries, food processing installations, cellulose plants, fish meal plants etc. Urban smells and odours usually originate from refuse containers and sewage system.

Sulphur dioxide is produced in burning of fossil fuels (coal and oil) in industries, thermal plants, homes, fertilizer industries and during smelting of metallic ores. The gaseous SO_2 oxidizes to SO_3, which in combination with water forms sulphuric acid. The major sources of sulphur dioxides are coal combustion of petroleum products, refuse burning, refinery operations and metallurgical operations. Sulphur dioxide and sulphur trioxide react with water to form sulphurous acid (H_2SO_3) and sulphuric acid (H_2SO_4), respectively. Aerosols are chemicals which are present in air in the form of vapours or fine mist. They are used as disinfectants. Fluorides are released during refinement of aluminium, rock phosphates etc. Gaseous fluorides cause necrosis, chlorosis and abscission of leaves etc. Air is normally used as the source of oxygen and nitrogen which combine at the temperature normally reached in the combustion process to form nitric oxide and then much of NO gets converted into NO_2. Nitrogen oxides are produced in the atmosphere electro-photo-chemically from nitrogen and oxygen. Biologically they are formed from nitrates and nitrites by denitrifying bacteria. These are also produced due to combustion process of fuel in industries, automobiles, nitrogen fertilizer plants etc. The major source of nitrogen oxides is automobiles, furnaces, boilers etc. Gas and coal fired furnaces, power station and common source combustion of wood as well as refuse waste also produce nitrogen oxides and ammonia. Hydrocarbons are produced naturally (e.g. marsh gas) and by evaporation from fuel dumps, incomplete combustion of fossil fuel, automobile exhausts, refineries, agricultural burning etc. Photo-chemical oxidants are produced photo-chemically by reaction between nitrogen oxides and hydrocarbons producing secondary pollutants like peroxyacyl nitrates, aldehydes and phenols. Ozone layer in the upper atmosphere (stratosphere) protects the living organisms from ultraviolet rays of the sun by absorbing nearly all of them. Smoggy fog produced by combination of smoke and fog causes glazing, silvering and necrosis of crops.

1. Acid Rain and Environment

SO_2 causes chlorosis, necrosis, plasmolysis, membrane damage, metabolic inhibition and death (Biggs and Davis, 1980; Alseher et al., 1987). Fluorides and Peroxyacyl nitrates damage leafy vegetables (NAS, 1971; Weinstein, 1977). Ozone and hydrocarbons cause pre-mature yellowing and fall of leaves and flower buds and discolouration and curling of sepals (Krupa et al., 1995; Heagle, 1989). Nitrogen oxides reduce yield of crops (Wellburn, 1981). Dust, Smoke and smog reduce sunlight and form a thin layer on the leaves, thereby retarding photosynthesis. Lichens are sensitive to air pollution. Sulfur dioxide emissions released into the air by factories, power plants and car, combine with water and water vapours in the atmosphere and fall onto the earth in the form of rain or snow (Rao and Rao, 1998). Similar to industrial air pollution, auto-exhaust pollution, in which oxides of sulphur, carbon, nitrogen, particulate matter, hydrocarbons and lead are present, also have phytotoxic effect. It changes the rate of photosynthesis, transpiration, reduction in chlorophyll content, thereby reducing the yield (Stern, 1973). Sulfur dioxide is the main industrial air pollutant which causes heavy damage to the vegetation and retards the growth of plants by stimulating abnormalities in metabolism of the plants, like photosynthesis, nitrogen and sulphur metabolism (Godzik and Krupa, 1982; Yadav and Chand, 1990). All these alterations ultimately result in the reduction of the yield.

The acid precipitation mixes with the rain clouds and makes it more acidic. This change is attributed principally to increased emissions of oxides of nitrogen and sulfur and their conversion to nitric and sulfuric acids (Galloway et al., 1976). The loss rate of SO_2 in faster than can be explained by gas phase chemistry alone as this is due to reactions of the liquid water droplets present in clouds. Sulphate (SO_4^{2-}) and nitrate (NO^-_3), the transformed products of SO_2 and NO_2 in the atmosphere, are largely responsible for acid rain. Rain also traps much of windblown particles, dust and other constituents, which may also be acidic (pH 2.5 to 4.8) in nature. Sulfuric acid (H_2SO_4), nitric acid (HNO_3), various sulphates and nitrates are the chief chemical constituents of these rains, though small amount of other acids like hydrochloric acids and their salts may also be present. Increase in the acidic substances in air due to various anthropogenic activities is increasing at an accelerated rate resulting in dramatic change in atmosphere leading to acidity of rain water, popularly called as acid rain.

Acid rain is the common name for acid deposition, such as rain, snow, sleet, hail and other forms of polluted precipitation. Acid deposition is a worldwide problem for all natural things including bodies of water, forests and other things and moving around the world. Acid precipitation has been reported in eastern North America, Northwestern and Central Europe, throughout Asia, and other scattered places around the World. Because more factories and refineries are being built, and the smokestacks are getting taller, the wind blows the polluted air to neighbouring countries, sometimes hundreds of miles away. Acid precipitation has a number of potential effects on terrestrial ecosystems including acidification of soils, altered nutrient supply, increased mobilization of aluminium and other shifts from acid sensitive to acid tolerant species of soil flora and fauna population, altered rates of decomposition of organics and nitrogen fixation (Jacobson et al., 1988). Foliar damage to crops and forests, interference with productivity processes, leaching of nutrients and other substance from leaves, increase or decrease in germination depending on sensitivity to acidity. Indirect effects on agricultural crops include fertilization by nitrate and sulphate promoting growth (Yang, 1989). Potential indirect effects on forests include acidification of forest soils and accompanying alternations in soil chemistry as well as reduced forest productivity and forest dieback. Potential effects on aquatic systems include acidification, decreased alkalinity and mobilization of aluminium and other metal ions. Other Biological effects on aquatic biota include altered species composition among plankton, vegetation and invertebrates, reduced population of decomposer organisms, decline in productivity of amphibians, fish skeletal deformities and increased mortality of fish. Increased fish kills may occur during heavy rains. Acid rain is highly interactive problem and the remedial measures to control it are prohibitively costlier. The main arguments against thermal power problem and the remedial measures to control it are prohibitively costlier. The main arguments against thermal power generation option are the potential of acid rain. It is again, desirable to control the pollution at the source rather than treating the effects of acid rain.

Acid rain's acid level is measured using pH scale (a 1-14 number scale), 1 being the most acidic and 14 being the most alkaline. A 7.0 is neither acidic nor alkaline, being known as distilled water and considered neutral, whereas on an average, a normal pH level for acid precipitation is around 5.6. Excessive amount of hydrogen ions adversely affects biological membranes, the electron transport system and a number of pH specific biochemical reactions. In higher plants, chlorophyll is degraded and leaves lose their green pigmentation, which results in drastic reduction in crop productivity.

2. Acid Rain Effects on Plant Growth and Development

The effects of acidic rains on the growth and development of plants are little understood (Evans, 1982), but nevertheless visible injuries and yield losses have been observed following treatments of simulated acid rain to crops in both, the laboratory and field situations. Field-grown soybeans provided with simulated rains in the range pH 4.1 to 2.7 in outdoor experiments (which excluded ambient rain), resulted in seed yields 3 to 23 % below those treated with rain of pH 5.6 (Evans et al., 1983; Evans et al., 1984). Evans et al. (1986) and Irving (1983) have reviewed the effects of acidic rain on crop growth and yield. Evans and Lewin (1981) and Evans et al. (1981) recorded reduced growth and yield of several crop species due to simulated acid rain (SAR) in greenhouse studies. Monocotyledons are reported to be relatively less affected by simulated acid rain (Evans, 1988; Kuittel and Pell, 1991). Young rootlets, leaves and shoots are typically more sensitive to low pH conditions but other metabolic aspects of the plants can be harmed as well. It also affects the compositions/makeup of soil water which is the main medium of nutrient supply for the plants and soil microflora. Acidic rain solutions enter the leaf tissue through the cuticle and produce variety of effects on plants (Wood and Borman, 1975) additionally. Greater leaf size/area results in greater interception of the simulated rain, increasing the possibility of injury.

The problem of acid rains has become an issue of concern for agriculturists.

Researches conducted using simulated acid rains (SAR) have shown that it may increase as well as decrease the productivity. Although vegetation and soil are the prime receptor of acid deposition and function as sink, the direct injury to vegetation is not reported in the literature. Studies using exposure of crop plants to simulated acid rain have shown that it may increase the yield or no effects on trees (Trioiano et al., 1983). Back et al. (1994) reported that simulated acid rain (pH 3.0) stimulates seedling growth in resort pine. The decrease in growth occurs when the acidity is due to sulfuric acid alone or together with nitric acid.

Among the plant metabolites, plant pigments are very sensitive to air pollutants and identified as indicator of the physiological states of plants stressed by acid rain (Sensor et al., 1990). The simulated acid rain not only changes the physical and chemical properties of soil but also toxic to the water bodies on open ground surfaces and also acidify the ground water through its continuous penetration thereby. The effects largely depend upon the normal mineralogical and organic makeup of the particular soil as well as other factors like rainfall amounts and slope of the growing surface. Buman (1985) has recorded a pH value of 3.8 for rainfall in Bombay. Johnston and Shriner (1985) reported that the impact of acid rain on wheat dry-weight differs among cultivars. Data for southern Ontario and sites in the north-eastern United States indicate that rain events with acidity of around pH 4.0 have been quite common and some as low as pH 3.0 occur occasionally (Chan, 1982; Evans, 1982; Evans et al., 1984). Several studies have been conducted worldwide on the exposure of various crop plants to acid rain and its ultimate effects on plant growth and reproduction are reviewed in next section.

Lee et al. (1981) made a comparative study to of response of major crops to sulfuric acid rain using potted plants grown in field chambers and exposed to simulated sulfuric acid rain (pH 3.0, 3.5 or 4.0) or to a control rain (pH 5.6). At harvest stage, the weights of the marketable portion, total aboveground portion and roots were determined for 28 crops. Of these, marketable yield production were inhibited for 5 crops - radish (*Raphanus sativa* L.), beet (*Beta vulgaris* cv. Cicla), carrot (*Daucus carota* L.), mustard greens (*Brassica juncea*), broccoli (*Brassica oleracea italica*), stimulated for 6 crops - tomato (*Lycopersicon esculentum*), green pepper (*Capsicum annuum* L.), strawberry (*Fragaria vesca* L.), alfalfa (*Medicago sativa*), orchardgrass (*Dactylis glomerata* L.), timothy (*Phieum pratense*), and ambiguously affected for one crop - potato (*Solanum tuberosum* L.). In addition, stem and leaf production of sweet corn (*Zea mays saccharata*) was stimulated whereas visible injury symptoms of tomatoes decreased their marketability. No statistically significant effects on yield were observed for the rest of 15 crops. The results suggest that the likelihood of yield being affected by acid depends on the plant part utilized, as well as on species. Plants were regularly examined for foliar injury associated with acid rain. Out of 35 cultivars examined, the foliage of 31 was injured at pH 3.0, 28 at pH 3.5 and 5 at pH 4.0. Foliar injury was not generally related to effects on yield however, foliar injury of Swiss chard (*B. vulgaris* cv. Cicla), mustard greens (*B. juncea*), and spinach (*S. oleracea*) was severe enough to adversely affect marketability.

Jacobson et al. (1985) investigated greenhouse-grown radish plants exposed to repeated applications of simulated acidic rain at pH values from 2.6 to 5.0 to estimate whether growth and yield responses to acidic rain change with stage of development and plants have the capacity to recover from injury during rain-free intervals. Acidic solutions contained sulphate to nitrate mass ratios of 2:1 and low concentrations of cations and anions common to rainfall of the eastern United States. One hour rain events were simulated by application of acidic solutions through rain nozzles to plants on rotating turntables. Seedling were found to be more susceptible to repeated applications of simulated acid rain than older plants as indicated by foliar injury and reductions in the dry mass of shoots and hypocotyls. However, exposures at an intermediate stage (rapid growth phase) caused the greatest reductions in dry mass of hypocotyls. A rain-free interval, after a series of exposures of simulated acidic rain, allowed plants to recover from injury and compensated for growth reductions. The capacity of plants to recover could be enhanced by lengthening the duration of rain-free intervals between exposures to simulated acidic rain. These observations indicate that the interaction of increased tolerance to acidity at certain growth stages and recovery from injury during rain-free intervals with the episodic nature of rainfall should be considered when determinations are made for reductions in yield from repeated exposures to rainfall with a pH sufficient to cause foliar injury below pH 3.4.

Caporn and Hutchinson (1986) observed *Brassica oleracea* L. (cabbage) exposed to simulated acid rains delivered as sprays at pH 5.6 - 2.8 and grown in glass house with controlled environment. A single rain treatment of pH 3.0 given to 10 days old plants elicited a marked downwards curvature in cotyledons (occurring within the duration of the 30 minutes spray). The cotyledon surface was extensively damaged following downward curvature. In contrast, similar treatments showed little or no injury in the older 'true' leaves. Estimate of the contact angles between rain drops and leaf surfaces, and Scanning electron microscopy of adaxial surfaces indicated that the contrasting morphology of the epicuticular wax on cotyledons and leaves was a major factor determining the extent of acid rain damage. Simulated acid rain treatment of pH 3.2 and 2.8 starting at the cotyledons stage, reduced plants growth by 17 to 15 % over a 20 days period, however, the same treatment given at later stages of development when the 'true' leaves were predominant, had no significant effect on growth. In the natural environment, the occurrence of highly acidic rain events during different stages of plants development may be an important determinant of the impact of rainfall on vegetation. The young seedling stage of species, such as *B. oleracea* where cotyledons show poor development of surface wax, may be particularly vulnerable.

DuBay (1989) used simulated acid rain treatments of pH 4.5, 3.5 or 2.5 after pollination and observed reduced percent seed setting in pot grown maize (*Zea mays* L.) in a green house by 7, 29 and 34 %, respectively. Compared to rain of pH 4.4, rain of pH 5.5 reduced seed set by 24 % compared to the no-rain control. Pollen germination and pollen tube penetration of the silk were complete by the time rain treatments began (one hour after pollination). Rain treatments applied just before pollination had no effect.

Porter et al. (1989) tested effects of simulated acid rain on soybean (*Glycine max* L.) cv. Amsoy 71 and Williams-82 treated twice in a week with 1.0 cm of 6 treatments ranging in pH 5.6 to 3.0. In cv. Amsoy 71, seed/plants, seed/pods and choff were reduced with increasing acidity and plants were shorter and non-lodging while in another cv. Williams-82, there was increase in seed oil content with decreasing pH. The magnitude of change was maximum to the tune of 6 % in susceptible cultivars and inconsistent between cultivars and year to year.

Banwart et al. (1990) screened 20 soybean (*Glycine max* L.) cultivars for their response to simulated acid rain of pH 3.0 and 5.6 but none of the cultivars tested were found to be extremely sensitive in terms of growth and yield reductions.

Singh et al. (1992) made pot experiment studies on the effects of endosulfan (Thiodan) and/or of solutions of water, sulfuric and nitric acids of pH 5.6, and 2.8 (to simulate acid rain) on *Vicia faba* (Faba beans). Both, acid rain and endosulfan reduced root and shoot lengths and numbers of nodules, except acid rain at pH 5.6 which showed better growth. The presence of endosulfan with the acid rain treatment increased breakdown of chlorophyll.

Hosono and Nouchi (1992) studied plants of radish (*Raphanus sativus*), spinach (*Spinacea oleracea*) and bush beans (*Phaseolus vulgaris*) exposed to simulated acid rain of pH 5.6 (control), 4.0 3.0 and 2.7 (or 2.5 in one experiment on radish and another of spinach) 3 times/week for 1 hour with 10 mm precipitation at a time. Visible injury occurred on leaves of all test plants exposed to acid rain of pH 3.0. Visible injury on cotyledons of radish and spinach and primary leaves of bush beans exposed to rain of pH 2.7 or 2.5 was severe and decreased growth of young plants compared with that of the control. Hypocotyls dry weight of radish plants exposed to rain of pH 2.5 was significantly smaller than those of the control. Pod fresh weight of bush beans exposed to rain of pH 2.7 did not decreased significantly. The results indicated that current mean annual levels of rain acidity over Japan (about pH 4.6) might not affect growth of these crops.

Kang and Kim (1992) studied Rice (*Oryza sativa*) cv. Tamjinbyeo and Somjinbyeo, Soybeans (*Glycine max* L.) cv. Beakun kong and Baekchun, and Sesame (*Seasmum indicum*) cv. Samdage and Suweon 128 exposed twice in a week to simulated acid rain of pH 2.6, 3.6, 4.6 or 5.6 (control). Acid rain caused no visible damage in either of these crops. In rice, the ripening ratio and grain yields decreased with increasing acidity of the simulated rain. Seed yield and 100-seed weight in soybeans were decreased by acid rain, while there were no significant effects in sesame. Soil pH decreased as pH of the simulated acid rain was decreased.

Chung et al. (1994) studied the effect of simulated acid rain of pH (2.5) sprayed on to cucumber (*Cucumis sativus* L.) and *Perilla frutescens* plants for 10 days at 10 mm per hour per day. Control plants were sprayed with distilled water at pH 6.0. *P. frutescens* turned very sensitive to the SAR in terms of plant growth (total leaf area, leaf DW and root DW were all significantly reduced) whereas cucumber proved resistant. Photosynthetic activity on per unit leaf area basis was not affected by SAR in either of the species. A marked increase in the wettability of *P. frutescens* leaves occurred within 1-2 days of SAR application. Severe epidermal layer degradation and cytoplasm depletion were also observed in the palisade cells of treated *P. frutescenes* leaves.

Hosono and Nouchi (1994) studied Radish (*Raphanus sativa* L.), spinach (*Spinacea oleracea*), bush bean (*Phaseolus vulgaris*), turnip (*Brassica rapa*), pakchoi (*Brassica chinensis*), lettuce (*Lactuca sativa* L.), carrot (*Daucus carota* L.) and rice (*Oryza sativa*) plants exposed to simulated acid rain at pH 5.6 (control), 3.0, 2.7 and 2.5. Treatments were imposed 3 times a week for 1 hour with 7-13 mm of simulated rainfall at a time. Simulated acid rain at pH 3.0 or below produced visible foliar injury on all tested plants. The degree of injury was greater on lower leaf positions, particularly cotyledons and primary leaves and foliar injury was more severe at the early stages of growth. DW of rice plants exposed to acid rain at pH of below 3.0 was reduced compared with pH 5.6 at the early stages of growth. During the middle to late growth stages, acid rain treatment did not affect rice growth. The yield of rice remained unaffected at pH 2.5.

Tong et al. (1994) studied rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) sprayed with water of pH 2.5, 3.5, 4.5, or 6.0 (simulating acid rain) during vegetative and reproductive stages. Rice grain yield was decreased by acid rain whereas wheat grain yield was slightly increased or showed a variable response.

Yao et al. (1996) studied the effects of simulated acid rain of pH 3.0, 4.0 and 5.6 on pollen grain germination and yield in rice (*Oryza sativa* L.) cv. Tainung 67 and Taichung sen 10. Pollen grain germination *in vivo* was reduced by up to 30 % and 10 %, respectively upon direct exposure to acid rain of pH 3.0 and 4.0. These reductions were associated with decreases in seed set, number of spikelet per panicle and grain yield. The pollen germination rate on agar medium at of pH 4.0 was 54 % of that grown at pH 5.6. At pH 3.0, there was almost no *in vitro* pollen germination. Effects of simulated acid rain were identical in the 2 cultivars.

Singh and Agrawal (1996) studied wheat (*Triticum aestivum* L.) cv. Malviya 206 and 234 (varying in cuticular thickness and leaf area) exposed to simulated acid rain field of pH 5.6 (control), 5.0, 4.5, 4.0 or 3.0 from 30 days of age, twice a week for five weeks. The plants received the acid rain treatment as well as ambient precipitation of unknown acidity. Shoot height, root length, and leaf area were reduced significantly in treated plants of different growth stages. Above and below ground biomass also decreased significantly in the plants treated with acidic precipitation. Relative to control, the number of grains/plant and yield/m^2 declined significantly at all acid rain treatments. The hypothesis “cultivar with thinner cuticle and greater leaf area would be more susceptible to acidic precipitation” was not supported by this study.

Fan and Li (1999) studied response of seeds and seedlings of 5 broad leaved species (*Cinnamomum camphora* L., *Castanopsis fissa, Ligustrum lucidum, Melia azedarach* L. and *Koelreuteria bipinnata*) separately exposed to simulated acid rain at pH values of 2.0, 3.5 and 6.0 or to distilled water. Germination recorded marked inhibition at the pH 2.0 for 3 species (*C. camphora, C. fissa* and *K. bipinnata*). At pH 2.0, significant foliar damage, decrease in chlorophyll contents, and retardation of seedling growth of all the species were evident. In fact, pH 2.0 seemed to be a threshold level for inhibition of seed germination and seedling growth for all the test plant species, since germination was similar to that of the control values at the less acidic pHs, while seedling growth was stimulated at pH ranging 3.5 to 5.0. Fan and Wang (2000) studied seeds and seedlings of 5 broad-leaved species (*C. camphora, C. fissa, L. lucidum, M. azedarach* L. and *K. bipinnata*) subjected to simulated acid rain treatments (pH 2.0, 3.5 and 6.0 and distilled water control). Seed germination was remarkably inhibited by the pH 2.0 treatment for 3 of the species (*C. camphora, C. fissa* and *K. bipinnata*). Significant foliar damage, chlorophyll decline, and growth retardation in seedlings of all the species were observed at pH 2.0, while seedling growth was simulated at pH levels between 3.5 and 5.0. The pH 2.0 treatment seemed a threshold level for inhibition of seed germination and seedling growth for all the treated species.

Pal and Kumar (2000) investigated effect of simulated acid rain treatments on yield and carbohydrate contents of *Capsicum* cv. NP-46 A. Flowering was promoted in SAR treated plants. Numbers of flowers and fruits per plant were decreased in treated plants for all treatments at all pH values, carbohydrate contents of stem and leaf fractions were affected adversely. The effect of simulated acid rain became more pronounced with increased acidity and duration of treatment.

Suneela and Thakre (2001) studied the responses of two Rice (*Oryza sativa* L.) IAT 9219 and IP 64 to simulated acid rain and selected chlorophyll contents, net photosynthetic rate, root and shoot length, percent phytotoxicity and dry matter of root and shoot and their ratio as biomonitoring indices. Among these chlorophyll contents, net photosynthetic rate and percent phytotoxicity served as good biological parameters for evaluating relative sensitivity.

Dursun et al. (2002) tested the effects of simulated acid rain (SAR; sulfuric acid based solutions with 4.5, 3.5 and 2.5 pH) on the yield and yield components of tomato (*Lycopersicon esculentum*) under greenhouse conditions. SAR was sprayed 27 times during the 75 day experiments. SAR with 2.5 and 3.5 pH induced wilting of leaves followed by the appearance of necrotic lesions on leaf surface. SAR with pH 4.5 and 5.9 were not injurious to plants. Generally, total yield, number of fruits, average fruit weight, and fruit diameter and weight decreased with the increase in SAR acidity. SAR also inhibited shoot growth, with the strongest inhibition recorded for SAR with 2.5 pH. Reductions in total yield and number of fruits at pH 2.5 (compared to 5.9) were significant (25 and 34 %, respectively).

Liao et al. (2003) studied the toxic effects of Cd^{2+} and acid rain on *Vicia faba* cv. Qidou. Cd^{2+} $(CH_2COO)_2$ was incorporated into the soil, resulting in a Cd^{2+} concentration of 4.0, 6.0, 8.0 or 10.0 mg/kg. Seedlings were transplanted two weeks later, and irrigated with distilled water (control) or simulated acid rain (pH 4.5 or 3.5). Crop injury, enzyme activity in leaves and roots and leaf cell ultra structure were studied before flowering. Seedling height recorded at 90 days decreased with the increase in Cd^{2+} content and with the reduction in pH value. The increase in Cd^{2+} concentration aggravated the reduction in plant height attributed to acid rain application. In general, seedling survival, and superoxide dismutase (SOD) activities in leaves and roots increased with the reduction in Cd^{2+} content and increase in the pH of acid rain. Injury symptoms were most pronounced in seedlings treated with 6.0 mg Cd^{2+}/kg and acid rain with a pH of 4.5. In these plants, the old leaves dried faster, and the number of lateral roots and root nodules were much lower. Root colour turned dark brown with increasing Cd^{2+} contents and decreasing pH of acid rain. Dead cells were observed in the outer layer of roots. Under severe pollution with Cd^{2+} and acid rain, the chloroplasts were deformed, the thyllakoids decomposed and numerous small black balls were scattered on the chloroplasts. Generally, SOD activity in leaves and roots decreased with the increase in Cd^{2+} concentration and in the reduction in the pH of acid rain. The reduction in SOD activity was more adverse in roots than in leaves.

Munzuroglu et al. (2003) treated the pollens of apple (*Malus sylvestris* cv. Golden) flowers with simulated acid rain solutions with pH ranging from 2.9 to 5.0 to determine its effects on the pollen germination and tube elongation. Pollen germination decreased by 41.75 % at pH 3.3, whereas pollen tube elongation decreased by 24.3 % at pH 3.4 as compared to the control (pH 6.5),. Acid rain threshold proportion value was around pH 3.3 and 3.4 for apple pollen germination and pollen tube elongation, respectively. Pollen tube elongation was more sensitive to acid rain than pollen germination. pH values below 3.1 resulted in complete destruction of pollen tubes whereas pollen germination entirely stopped at around pH 3.0. It revealed that ‘acid rain has a blocking effect on pollen germination and pollen tube elongation in apple’ and pH values, as well as the quantity of acid rain are important factors in germination. The results were found statistically significant through the LSD test at levels of $p<0.05$ and $p<0.01$.

Tyagi et al. (2004) conducted an experiment to determine the effects of simulated acid rain (pH 5.6, 4.5, 3.5 and 2.5) on the seedling growth of peas (*Pisum sativum*), the root and shoot length decreased with an increase in pH, except for pH 4.5. The fresh and dry weight of the root and shoot were also inhibited by acidity and the same was true for root weight, shoot weight and root: shoot ratio. Simulated acid rain with a pH of 4.5 enhanced seedling growth.

Singh and Agrawal (2004) reported a field based experiment conducted to assess the effect of simulated acid rain of different pH i.e. 5.6 (control), 5.0, 4.5, 4.0 and 3.0 on two wheat (*Triticum aestivum*) cultivars Malviya 213 (M 213) and Sonalika). Shoot and root lengths significantly declined at pH 3.0 in both varieties. Leaf area declined at pH 4.0 and 3.0 in M 213 at both the ages and at 75 days in Sonalika. Biomass of 75 days old plants declined significantly at pH range 4.5-3.0 in M 213 and at pH 4.0 and 3.0 in Sonalika. Net assimilation rate (NAR) declined significantly at pH 3.0 in both varieties. Compared to control, yield of M 213 showed significant reductions at pH 4.0 and 3.0, whereas Sonalika responded negatively at pH 3.0. The study showed that acid rain has a significantly negative effect on wheat plant performance.

Imran and Hussain (2004) conducted a greenhouse experiment to study the effect of simulated acid rain (SAR) of sulfuric acid and nitric acid, alone and in combination, with different pH values on the morphology of Mash (*Vigna mungo*) cultivars 95009 and Mash-97 during early growth. The treatment comprised: rain water only (acid level 0); sulfuric acid at pH 5.5 (acid level 1); sulfuric acid at pH 4.5 (acid level 2); sulfuric acid at pH 3.5 (acid level 3); nitric acid at pH 5.5 (acid level 4) nitric acid at pH 4.5 (acid level 5) nitric acid pH 3.5 (acid level 6); sulfuric acid + nitric acid at pH 5.5 (acid level 7); sulfuric acid + nitric acid at pH 4.5 (acid level 8); and sulfuric acid at pH 3.5 (acid level 9). Maximum shoot length (26.19 cm) was observed in acid level 6. Cultivar x acid level interaction significantly differed as the maximum value (28.78 cm) was recorded in acid level 6 treated 95009. The maximum root length (18.47 cm) was observed with acid level 9. The cultivar x acid level interaction showed significant differences as maximum value (20.78 cm) observed in acid level 9 treated 95009 cultivar while the minimum value (11.25 cm) was observed with acid level 3 treatments. The acid level means revealed that the maximum number of leaves (8.96) was observed in acid level 0 and minimum (6.72) in acid level 9, while cultivar x acid level interaction showed non-significant differences. The maximum number of leaves (9.53) was observed in acid level 0-treated 95009 while minimum (6.23) in acid level 9-treated Mash-97.

Kumaravelu and Ramanujam (2004) studied ten day old plants of green gram (*Vigna radiata* (L.) Wilczek) cv. ADT-1 and Vamban exposed to simulated sulfuric acid rain (SAR) of pH 5.5, 4.0, 2.5 and 7.0 (control) for 5 consecutive days to determine their effects on growth and yield. The acid showers of pH 5.5 and 4.0 favoured plant growth in both the cultivars. The photosynthetic pigments, soluble protein, reducing and total sugars and starch in both cultivars were higher at pH 5.5 and slowly decreased with increasing levels of acidity. The acid rains of pH 5.5 and 4.0 substantially increased the number of pods and seeds per plant in both cultivars. However, the acid rain of extreme acidity (pH 2.5) was inhibitory. Vamban was more sensitive than ADT-1 to acid rain.

Huang et al. (2005) studied ten years old trees of *Clausena lansium* cv. Jixin Wampee sprayed 3 times (once every 10 days) with simulated acid rain of different pH values (5.6, 4.0, 3.0 and 2.0). Acid rain was found to inhibit shoot elongation, but enhanced shoot thickness. Acid rain at pH value 3.0 or below resulted in lower fruit quality. The effects of different pH values of acid rain on shoot and fruit growth and development are decreased significantly.

Zeng et al. (2005) studied on Rice, wheat and rape seeds treated with simulated acid rain at pH 2.0, 2.5, 3.0, 3.5, 4.0 and 5.0 levels for 7 days in order to understand the effects of acid rain on seed germination of various acid-fast plants. Seed germination was absolutely inhibited at pH 2.0 for three test species. Rice and wheat seeds germinated abnormally at pH 2.5. Germination, germination energy, germination index, vigor index of rice, wheat and rape seeds increased above pH 3.0 in relation with decreased acidity levels. In contrast, the percentage of abnormal germination of rice and wheat decreased. The data about physiological aspect demonstrated that water absorption rate, respiratory rate and storage reserve transformation rate of rice, wheat and rape seeds also increased with increasing pH. The storage loss of rice and wheat increased with increased pH but that of rape decreased. Inhibition index of shoot and root length of three kinds of seeds decreased in relation with increased pH values. The amplitude difference of index of rice was lower than wheat, and wheat was lower than rape. The data revealed that rice had stronger fastness than wheat and rape, and wheat had stronger fastness than rape under acid rain stress.

Sirohi and Khan (2006) conducted a field experiment to investigate the effect of acidification on the environment and on fodder crop *Trifolium alexandrium* cv. Mascot grown in nearby agricultural fields. Samples of ambient rain water were collected during the rainy seasons of 2003, 2004 and 2005. Emission of SO_2 was increased from 2002 to 2004 but decreased in 2005, however, suspended particulate matter (SPM) decreased after installation of high efficiency electrostatic precipitators in Jubilant Organosys Ltd. and Efficiency Scrubber in the single super phosphate plant at Gajraula due to decreased pH (5.0) of acid rain water. Germination percentage of 83.33, 86.66, 96.33 and 96.66 were observed at pH 2.0, 3.0, 4.0 and control, respectively. Seedling height showed a decreasing trend at pH 4>3>2. There were significant decreases in the length of root and shoot at pH 4.0, 3.0 and 2.0 in 15 days-old plants. Fresh and dry weight of shoot and root revealed the same trend. Necrotic lesions were first observed on the leaves of the plants treated with pH 2.5 after 40 days. Total leaf area of the plants exposed to simulated acid rain was also reduced significantly. There was a negative correlation between growth index and phytotoxicity percentage. The growth index decreased at all pH levels of acid rain in comparison to control.

Pragati and Dhaka (2006) investigated plants of *Zinnia elegans* sprayed with simulated acid rain (pH 5.6, 4.5, 3.5 or 2.5) prepared using a mixture of sulfuric acid and nitric acid (3: 1). Root and shoot lengths, fresh matter, and dry weight decreased as the pH of the acid rain decreased and the duration of exposure increased. The reduction in dry matter was greater in roots than in shoots.

Mai et al. (2008) conducted a field experiment to estimate simulated acid rain stress effects on growth and development in winter wheat cv. Yamgmai 12 and observed that simulated acid rain had considerable effect on wheat growth and yield. The growth of leaf area as well as the mass of fresh leaf per unit area declined greatly at pH 3.5, and the yield was significantly lower than control. The plant height was obviously lowered, and the visible injury on leaf surface was observed at pH 2.5. Under acid rain stress, leaf chlorophyll a, chlorophyll b and carotenoid contents, especially chlorophyll a decreased obviously. Acid rain also suppressed the synthesis of soluble sugar and reduced sugar, and the suppression was stronger at pH 3.5, and became much stronger with increasing acidity. The total free amino acid and soluble protein contents in leaves decreased with increasing acidity, and were significantly lower than control when the pH was 3.5 and 4.5, respectively. In a similar study using simulated acid rain of pH 5.7, 4.5 and 3.0, Lal and Singh (2015) observed that acid rain caused a marked decline in Chl a, chl b and carotenoids in sunflower leaves at peak growth stage.

Liang et al. (2008) studied the simulated acid rain at pH 5.6 as the control index (CK), by means of H_2SO_4 and HNO_3 at the ratio of 5 to 1 as the concentration for the rain at the levels of pH 1.5, 3.1, 4.1, 5.1 and 5.6 measured in rape cv. Qinyou 7. The

15 plots (4 m×5 m) were divided into 5 treatment groups i.e., (1) CK (pH 5.6), (2) extreme AR (pH 1.5), (3) strong AR (pH 3.1), (4) moderate AR (pH 4.1), (5) weak AR (pH 5.1), each repeated in spraying thrice. Starting from the 3-leaf stage, small-size sprayers were used to water the plants at a 10-day interval, separately, with above 5 acid rains as natural precipitation. In the field experimental period, the rape growth and development were recorded up to flowering stage; measurement was made of plant height, leaf area, weight of 1 cm^2 fresh leaves and injured area in percentage etc. and also of the yield and quality during harvest. Results show that (1) simulated acid rain stress has considerable effect on the rape growth/development in such a way that the plant height and leaf area are suppressed and weight of fresh leaf per unit area is greatly declined with visible injury when pH 3.1 operation is conducted; (2) yield analysis indicates that pH 4.1 concentration can be taken as the threshold value of the effect on rape yield; (3) study of quality indexes shows that acid rain stress can reduce the content of crude fat and soluble sugar in the seeds, and with increased acidity their drop ranges will enlarge. The stress influences the soluble protein at pH 5.1-4.1, total free amino acid content at pH 4.1-3.1, as well as reduced sugar, and total acidity at pH 3.1-1.5. The specific values of above indexes as well as the mechanisms for their effect on acid rain concentration remains to be further explored.

Shaukat and Khan (2008) investigated the effect of simulated acid rain (SAR) on growth, yield and physiological parameters in tomato. SAR exposure (pH 3.0 and 4.0) caused white-to-tan spots on the abaxial and adaxial surface of tomato leaves. SAR exposure at pH 3.0 and 4.0 significantly inhibited pigment synthesis, shoot and root dry weights and yield. The effects were more pronounced at lower pH 3.0. Reducing and nonreducing sugars were diminished significantly to varying degree by SAR solutions of pH 3.0 and 4.0 and the effect being more accentuated at pH 3.0. Non-reducing sugars declined to a greater extent than did the reducing sugars and this effect were more pronounced in SAR-treatment of pH 3.0. SAR-exposure of pH 3.0 and 4.0 resulted in accumulation of soluble phenols as an induced mechanism against SAR stress.

Kausar and Khan (2009) studied interaction of different SAR doses (pH 3.0, 4.0 and 5.0) with different inoculum levels of *Anguina tritici* on wheat plants. Both SAR and *A. tritici* interacted antagonistically. The wheat plants inoculated with lower inoculum levels (2,500 and 5,000) and exposed with lower acidity level (5.0) were not affected in terms of plant growth, yield, photosynthetic pigments, seed carbohydrate, seed protein and leaf epidermal characteristics compared to un-inoculated and un-exposed plants. While, the suppressions in all above parameters were increased with increase in acidity level (pH 4.0 and 3.0). However, nematodes were killed by SAR except in treatments with lower dose and higher inoculum levels (5.0 + 5000 and 5.0 + 10000), where few galls were formed.

Han (2009) studied effect of acid rain at different pH (1.0, 2.0, 3.0, 4.0, 5.0, 6.5) on seed germination and seedling growth of *Vigna unguiculata* ssp. *sesquipedatis* (L.) Verdc. Seed germination rate, germinated vigor, germination index, seedling root length and hypocotyl length tended to decrease with the decrease in pH. All *V. unguiculata* ssp. *sesquipedatis* (L.) Verdc seeds were musty when pH was 1.0.

Verma et al. (2010) studied the impact of simulated acid rain with pH levels of 5.0, 4.0 and 3.0 on three popular vegetable plant species viz. *Capsicum annuum*, *Lycopersicon esculentum* and *Solanum melongea*. The species were raised in earthen pots with agriculture soil. Chlorophyll contents were more or less unaffected in all the three species but the growth parameters and fruiting was severely curtailed with increasing acidity.

Kausar et al. (2010) reported that simulated acid rain (SAR) exposure caused adverse effect on morphological, biochemical and leaf epidermal parameters of wheat cv. HD-2329. Plant growth (length, fresh and dry weight of shoot and root; tillers number, leaf area) and yield parameters (ear length, numbers of grains/ear and weight of 100 grains) were suppressed significantly at SAR levels of 3.0, 4.0 and 5.0 pH. Highest suppressions were reduced at pH 3.0 level compared to control. Photosynthetic pigments (Chl a, Chl b, total Chl and carotenoids), seed carbohydrate (soluble and insoluble), seed protein (soluble and insoluble) as well as leaf epidermal parameters (number of stomata, stomatal aperture and length of trichomes) also decreased significantly with the increase of acidity.

Lal and Singh (2012) studied effects of simulated acid rain of different pH [distilled water-7.0 (control), 5.7, 4.5 and 3.0] in sunflower (*Helianthus annuus*) cv. 'Morden' and evaluated its effects on plant root, shoot and leaf at peak growth and maturity stages. Their results revealed that biomass and lengths of the studied plant parts decreased with decreasing pH of acid rain solution. Comparison of biomass and length at peak growth and maturity stages recorded maximum difference in control and the difference narrowed with increasing acidity. The differences at acidic treatments were well-marked with leaves followed by roots and shoots, respectively. In case of length, roots and shoots were more adversely affected as compared to leaves. Acid rain application caused reduction in leaf area which has direct bearing on growth of roots and shoots, and overall plant growth. Effects of SAR on sunflower increased more dramatically with the increase of SAR acidity and were correlated with exposure times and doses of SAR.

4. Concluding remarks and future perspectives

The above survey of literature demonstrates that natural and simulated acid rains affect the germination, growth, biomass, behavior of budding, flowering and leaf abscission, photosynthesis, metabolic processes, enzymes activities, cytoplasm properties, pollen behavior and yield in range of plant species. An important aspect of plant life is the germination process and seedling growth that forms the health/foundation for subsequent stages. SAR effects at these stages are likely to have short-term as well as long-term effect on plant life (growth and yield). It is evident from the literature that most of the crop plants are sensitive to acid rain, there is an urgent need to identify/develop suitable cultivars suited to acid rain affected zones. The concentration of acid rain may further increase due to an extent causing an acidification of cytoplasm to decrease intracellular pH. The capacity of acidic buffering and the mechanism(s) involved in SAR treated plant systems are still unclear and require deeper investigations.

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