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Acid Rain: A Review

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Annotation: Around the world, acid rain (AR) has a complex harmful impact on plants and produces a variety of other environmental problems. Several previous studies have examined the direct impact of AR or its depositional components on plant damage and performance. The indirect effects of AR on plants, which are mediated by soil microorganisms and the abiotic environment of the soil rhizosphere, have not been well investigated, acidic deposition affects not only the distribution, composition, abundance, function, and activity of microorganisms associated with plants, but also the dynamics of certain substances in the soil, which may be detrimental to plants. Therefore, the indirect effects (AR → soil and water → plants) require more attention. The AR-soil chemical characteristics-plants route shows how soil solute leaching and acidification by AR would lower the availability of vital nutrients and increase the availability of heavy metals for plants, impacting the carbon and nitrogen cycles was therefore covered in this review in addition explores the direct impacts of AR on plant performance, growth, and biomass allocations on a whole-plant scale.

Keywords: Acid rain, Environment, Plant, Microorganisms, Soil.

1. Introduction

Acid rain (AR) contamination has often resulted in environmental disasters and monetary losses globally from the start of the industrial revolution [1,2], typically, emissions from human activities—such as burning coal, industrial output, and Vehicle exhaust emits acidic chemicals such as sulfur dioxide (SO2) and nitrogen oxides (NOx)[3,4]. Natural processes including volcanic eruptions, lightning-caused forest fires, and ocean foam produce sulfur oxides (Sox), concentrated sulfuric acid (H2SO4), and other acidic chemicals [5,6]. The process by which acidic chemicals react with atmospheric moisture to generate acid precipitation is known as AR (pH < 5.6). These substances have the ability to travel long distances and finally deposit acid on the earth [7,8]. Acid rain may erode infrastructure and reduce forest habitats, as well as reduce crop yields and acidify soils and aquatic environments [9].

In terrestrial ecosystems, Plants are crucial for biodiversity and production in addition to serving as the main sensors and interceptors of AR pollutants. Thus, plant response patterns to AR can help researchers with a solid theoretical basis for tackling associated challenges and assist land managers in developing technical remedies employed in the restoration and rebuilding of degraded ecosystems in AR-affected regions [10,11]. Plant performance is directly impacted by AR's acidity. According to simulation studies, simulated AR (SAR) treatments reduce photosynthesis and growth by inhibiting the growth and development of the above-ground (leaf) and below-ground (root) organs of plants, respectively. There has been much research on the direct effects of AR's acidity as well as the indirect effects of AR-mediated soil chemical characteristics on plants [9–12].

High AR frequencies significantly decrease Soil microbe biomass, diversity, and activity, rhizosphere microbes possess the capacity to affect how AR pollutants that have been deposited in soil are transformed; Additionally, they could trigger the release of plant hormones, containing indoleacetic acid, which, in the presence of AR stress, can regulate growth and reproduction [13,14] , Microorganisms are a fundamental component of soils and play a critical role in moderating AR's effects on the soil-plant system. However, there was a dearth of previous study on the AR-soil microbe-plant pathway, the majority of plant species form root symbioses with arbuscular mycorrhizal fungus (AMF), and ectomycorrhizal fungi (EcMF), which significantly affect plant development and response to environmental stresses like AR. For instance, it has been demonstrated that the addition of nitrogen (N) has a detrimental effect on several AMF guilds, which is influenced by the pH of the soil [15,16]. Likewise, it is well recognized that N deposition has a detrimental effect on EcMF colonization of roots. However, by inoculating plants with AMF and EcMF, for example, symbiotic microbes can mitigate heavy metal toxicity and other negative impacts of AR in plants. Numerous meta-analyses have already shown how harmful nitrogen deposition and acidic stress are to soil that is connected with plants microorganisms; But little focus has been placed on how various plant mycorrhizal species react to AR stress. [17–19]. The current study aims to know the effect of acid rain on the environment, especially plants, through the direct effect on them or indirectly through the effect on soil and water.

2. Acid rain

Acid rain is any precipitation, including rain, that has a low pH (high concentration of hydrogen ions), while most water, including drinking water, has a neutral pH of 6.5 to 8.5, acid rain has a pH lower than this, usually between 4 and 5 [20]. The pH of acid rain drops as the acidity increases. Acid rain has a harmful influence on infrastructure, marine life, and vegetation.

Emissions of nitrogen oxide and sulfur dioxide interact with atmospheric water molecules to produce acids, causing acid rain [21].

Forests, freshwaters, soils, microorganisms, insects, and aquatic life-forms have all been demonstrated to suffer negative effects from acid rain [3]. Prolonged acid rain weakens tree bark in ecosystems, making flora more vulnerable to environmental stresses including pest infestation, heat, and cold, as well as drought. By depriving acid rain can deplete the soil of components such as calcium and magnesium, which are required for plant development and soil health. It can also have a deleterious influence on soil composition. In addition to its impact on human health, acid rain corrodes steel structures such as bridges, weathers stone buildings and sculptures, and causes paint to peel [7,22].

Since the 1970s, several governments, such as those in North America and Europe enforcing air pollution legislation has helped to reduce the quantity of nitrogen oxide and sulfur dioxide discharged into the atmosphere [23]. These efforts have been successful because of the substantial studies on acid rain that started in the 1960s and the widely shared knowledge about its harmful effects. Even though human activity is primarily responsible for the sulfur and nitrogen compounds that generate acid rain, lightning strikes can also naturally produce nitrogen oxides, and volcanic eruptions can produce sulfur dioxide [23, 24].

2.1. Effect acid rain on surface waters and aquatic animals

Numerous effects of sulfuric and nitric acids on aquatic environments include acidification, elevated levels of nitrogen and aluminum, and modifications to the biogeochemical processes [25]. Fish and other aquatic life may be harmed by the lower pH and increased aluminum concentrations in surface water brought on by acid rain, most fish eggs do not hatch at pH levels below 5, and adult fish can be killed by lower pH levels. Biodiversity declines when rivers and lakes become more acidic. In certain lakes, creeks, and streams in sensitive geographic areas, such as the US Adirondack Mountains, acid rain has killed out bug life and certain fish species, including brook trout. [15,25]. However, there is variation in the degree which acid rain, directly or indirectly affects lake and river acidity through runoff from the catchment (i.e., depending on the surrounding watershed features). "Of the lakes and streams surveyed, acid rain generated acidity in 75% of the acidic lakes and roughly 50% of the acidic streams" [25] according to the US Environmental Protection Agency's (EPA) website. Even with the same quantity of acid rain, lakes that are hosted by silicate basement rocks have a higher acidity than lakes that are hosted limestone or other carbonate-rich basement rocks, such as marble, due of the buffering properties of carbonate minerals [23].

2.2. Effect acid rain on soils components

The chemical and biological processes that occur in soil can be seriously disrupted by acid rain. For example, microorganisms that cannot tolerate acidic environments cannot adapt to the soil's lower pH and ultimately die [26]. The acidic environment then denatures the enzymes of these microbes. Additionally, it is thought that several nutrients that are necessary for plant life—magnesium being the most notable example—are leached away by the increased concentration of hydrogen or hydronium ions in the soil (as a result of acid rain) [27]. A higher concentration of hydronium ions in the soil can also cause some poisons to be released; aluminum is the most prominent example of this [28].

Acid rain can cause significant harm to the chemistry and biology of soil. Certain microorganisms are killed when their pH drops because they cannot withstand the changes [28]. The acid denatures these microorganisms' enzymes, changing their structure to prevent them from functioning. In addition to mobilizing pollutants like aluminum, acid rain's hydronium ions also remove vital minerals and nutrients like magnesium [5].

$$2\,H^+ (aq) + Mg^{2+} (clay) \rightleftharpoons 2\,H^+ (clay) + Mg^{2+} (aq)$$

Acid rain leaches base cations, including calcium and magnesium, it can drastically alter the chemistry of the soil, impacting sensitive species like sugar maple (Acer saccharum) [22].

2.3. Effect acid rain on plants

2.3.1. AR's direct impact on the physiology of plans and growth rate

AR's impacts on the micromorphology of leaf blades include the breakdown of epidermal cells and the waxy surface structure, which could have a number of negative implications on plant photosynthesis. AR, for instance, can result in stomatal distortion, partial spongy tissue collapse, and epidermal collapse. [29, 30]. Since stomata are the primary pathway for transfer of gases in plants, their dysfunction will have a negative impact on the growth and development of the plant , genipa Americana leaves' mesophyll and epidermal cells, for instance, start to shrink at pH 3.0, according to Sant'Anna-Santos et al. (2006). The spongy tissue cells undergo hypertrophy first, followed by the accumulation of phenolic compounds and starch granules [29,30].

Acid rain can damage organelles like mitochondria and chloroplasts by upsetting the mesophyll tissue and organelles in leaves. AR, for instance, can break down cell membranes and walls, creating mitochondrial ridges in between bigger inclusions [31].

A considerable decrease in leaf chlorophyll content was seen when the pH was decreased by an AR treatment, which directly hindered photosynthesis and the buildup of plant organic matter [32]. Furthermore, AR damages chloroplasts, erodes wax on the surface of the leaf, and causes base cation leakage in mesophyll cells caused by acid. Certain plant taxa, life stages, and treatment pH levels are associated with AR's effects on plant photosynthesis [33, 34]. As treatment pH rose, it was observed that the amount of chlorophyll in the leaves increased. Furthermore, as the pH of the AR treatment dropped, the amount of chlorophyll in the leaves of both woody and non-woody plants dropped as well. The slope of log response rates fell more sharply at low treatment pH, suggesting found plants that weren't woody were more vulnerable to AR than those that were. This could be because woody and non-woody plants have different leaf surface properties [10,35].

Numerous changes permeability of plant membranes, enzymatic activity, the production of metabolism, free radical antioxidants, and have been demonstrated to be brought on by acid rain [36]. Reactive oxygen species (ROS) and other free radicals are eliminated by plants via both enzymatic and nonenzymatic processes. The initial layer of protection from antioxidants is superoxide dismutase (SOD). The second line of defense, catalase (CAT), scavenges H2O2, which is generated within the cell [37, 38]. Cells can be shielded from elevated ROS concentrations by peroxidases (POD). These enzymatic systems have the ability to preserve the redox state of cells while also safeguarding their structure and functionality. AR would, nevertheless, have an impact on plant leaves' SOD, POD, and CAT. It was discovered that as the acidity generated by AR increased, spinach leaves' SOD activity decreased [39, 40]. Another study revealed a hump-shaped curve in the activities of SOD, POD, and CAT, which first increased in wheat and subsequently decreased when the pH of AR decreased. Therefore, Low PH treatment of SAR may affect and interfere with defensive systems in plants, which in turn increases membrane permeability, depending on a species' ability to tolerate AR stress. [18, 39].

2.3.1.1. Plant diseases and insect infestations brought on by AR

The leaf's capacity to defend itself is diminished when AR destroys cells in the plasma membrane and epidermis, which makes it easier for bacteria, fungus, and pathogens to infiltrate and damage the leaves. Nonetheless, there may be intricate connections among AR, plant illnesses, and insect pests. While AR can also block certain plant diseases and insect pests, hence reducing their spread, the damage it causes creates a handy conduit for disease and insect infection [41]. For instance infectious bacterial inoculation after the development of leaf spot can worsen plant diseases in tomato plants that were initially treated with SAR. If the germs are experimentally injected first, followed by SAR treatment of the plants, some illnesses can be reduced since AR can inhibit the growth of harmful bacteria. By lowering sporulation and lowering pH 3.5 treatment can considerably increase the incubation period of wheat yellow rust disease, as shown by the area under a disease progression curve [42, 43].

2.3.2. Indirect effects of AR on plants

Known as the AR-soil chemical properties-plant interaction, acid rain has been demonstrated to alter the concentrations of certain ions in the soil, which may further impact Plant roots absorb nutrients from the earth [44]. The majority of studies have shown the long-term ion leaching causes a nutrient shortage in the soil and that acid deposition speeds up the leaching of base cations. In addition to decreasing the soil buffering capacity and increasing cation leaching from forest soils, nitrogen deposition also increases soil acidity through two mechanisms: (1) the direct effects of nitric acid; and (2) the formation of H^+ ions by the nitrification of ammonia in soil [45]. By decreasing the availability of vital nutrients (like P and N) and increasing the availability of heavy metals (like cadmium and lead), acidic soil may alter the soil environment and have an impact on plant growth and metabolism. Additionally, too much nitrogen in the soil causes base ions to drain more readily, creating a nutritional imbalance in the forest that eventually causes destruction [46].

Acid rain seeps into soil particles, removing the soil's basic cations and replacing them with acidic cations such as H+ and aluminum ions ($Al^{3+),}$ and Mn^{2+}. This leads to issues with soil acidification [47]. The N cycle, N fixation, and the absorption of available phosphorus (P) are all impacted, either directly or indirectly, by the rise in Al^{3+} concentration in soil solution and the resulting soil acidification, which negatively impacts plant physiology and growth [48].

The heavy metal ions released by acid deposition, together with their quantity, speciation, composition, and bioavailability in the soil, will also be impacted by the processes of nutrient leaching and soil acidification. For instance, low pH and too much Mn^{2+} dramatically decreased cucumber roots' CAT activity [49]. One of the most hazardous elements found in soil is cadmium (Cd^{2+}). Low pH 3.0 brought on by AR and a high concentration of Cd^{2+} (100 mg/kg) in combination treatments can reduce plant biomass overall and alter the distribution of biomass across various plant organs. In addition to further suppressing photosynthesis and lowering biomass, the other combination therapies with AR and a high concentration of Cd2+ decreased the amount of Fe3+ and Mg2+ in the soil [49,50].

3. AR-soil microorganisms-plants

Microbes affect the growth and survival of plants, according to earlier research. For instance, rhizosphere microbes have the ability to control soil nitrogen levels and trigger the release of plant hormones, like indoleacetic acid, by plants to control development and flowering [14]. Furthermore, long-term co-evolution has improved the relationships between plants (such as agricultural crops) and their symbiotic bacteria, enabling them to adjust to stressors and environmental changes [32, 51]. Another significant mechanism that has an indirect impact on plants is the interaction between acid rain, soil microbes, and plants. Both roots and soil microbes are poisoned by the H+ in SAR. Plant physiological activities may be further impacted by declines in the soil microbial population's activity, community structure, and functional diversity when there is a high concentration of H+ ions in the soil [52,53].

The variety, biomass, and functions of soil bacteria can all be adversely affected by acid rain. For instance, a high frequency of AR dramatically reduces soil microbial biomass, particularly gram-negative bacteria in forest soil whereas AR may significantly change soil microbial biomass [13]. Excessive nitrogen deposition has been shown to reduce the microbial biomass of both carbon and nitrogen in subtropical forests. Plant performance may be impacted by acid rain since it can reduce the survival of soil nitrogen-fixing bacteria (SNB) and Rhizobia [55].To a certain degree, AM fungus can improve plant N fixation and accessible P absorption. However, environmental stress caused by strong acids may hinder this process and impair fungal and plant development, affecting the roots' capacity to absorb available phosphorus from the soil [47]. Additionally, through symbiosis with various mycorrhizal fungi, plants had varying reactions to AR. According to the meta-analysis, plants that coexisted with various mycorrhizal species showed variations in their characteristics or reactions to the acidity of AR treatment. According to earlier research, plants inoculated with either AM or EcM fungus can successfully boost a particular plant's resistance to AR stress [40, 55]. For instance, by increasing substrate availability, EcM fungal inoculation may mitigate the adverse impacts of AR on the microorganisms' N-cycling process in forest soils. But compared to EcM plants, AM fungi appear to be more susceptible to acidic soil, which is less helpful for promoting plant development and nutrient absorption (observe the almost neutral overall effects of treatment pH on EcM plants). Through symbiosis with ectomycorrhizal fungiEcM plants may benefit from both chemical and physical protection provided by the mycelial structure, this might explain the distinct roles that AM and EcM play in mediating the effects of AR on plants [13,55].

AR, plants, and soil bacteria have a complicated connection. According to a few studies, many bacteria associated with plants are eosinophilic, meaning that they may adapt to varying acidity levels and grow more active with AR in certain situations. As a result, AR further enhances plant performance [46]. In addition to the ways that AR indirectly impacts plants, we advise focusing further on how AR impacts the symbiosis of plant microorganisms (such as soil nitrogen-fixing soil bacteria, AM, and EcM fungus).

4. Conclusion

An important global research subject pertaining to how plant production and performance react to stress caused by decreasing acidity is the investigation of AR's impacts on the soil-plant system. This overview provides more thorough views for future research by summarizing and analyzing the direct impacts of AR on plants as well as the indirect effects of AR-soil chemical characteristics/soil microorganisms-plant. Consistent with earlier research, we provided proof that AR has a direct impact on plant reproduction and performance. We also showed how AR changes the microbial composition pathways and the chemical properties of soil, which indirectly affects plants.

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