

The Impact of Acid Rain on Crops and Countermeasures

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Abstract. This paper examines the contributing factors to acid rain formation, its effects on crops, and relevant research developments. The formation of acid rain is influenced by both anthropogenic and natural factors. On the anthropogenic side, industrial production, residential fuel combustion, and the emission of sulfur and nitrogen oxides from motor vehicles all contribute to its generation. On the natural side, volcanic eruptions and the decomposition of flora and fauna may also play a role. Acid rain poses significant threats to crops: it accelerates soil acidification, alters soil structure, disrupts microbial populations and nutrient cycles, and causes direct damage to crops. Different crop species exhibit varying sensitivities to acid rain. Recent research has made considerable progress in elucidating the mechanisms of harm and exploring prevention and control strategies, which holds significant implications for mitigation efforts.

Keywords: Acid Rain, Crops, Acidification

1. Factors contributing to the formation of acid rain

1.1. Anthropogenic factors

The formation of acid rain is largely influenced by human activities. During industrial production, the extensive combustion of fossil fuels such as coal and petroleum releases large quantities of sulfur and nitrogen oxides. For instance, industrial enterprises such as power plants, steel mills, and smelters emit significant amounts of sulfur dioxide during their operations. In addition, the combustion of coal, oil, and natural gas for residential purposes—such as the use of small household coal stoves—also generates sulfur and nitrogen oxides. Moreover, motor vehicle exhaust is another major contributor to the formation of acid rain. Vehicle emissions contain substantial amounts of nitrogen oxides, which react with other substances in the atmosphere to form acidic compounds.

1.2. Natural factors

In addition to anthropogenic influences, certain natural phenomena can also contribute to the formation of acid rain. The horizontal and vertical dispersion of pollutants varies under different meteorological conditions [1]. Volcanic eruptions, for instance, release large quantities of sulfur compounds into the atmosphere. These substances undergo in-cloud processes and below-cloud scavenging, ultimately leading to the formation of acid rain. Specifically, water vapor condenses on

certain nuclei—such as sulfate ions—followed by oxidation reactions that result in acidic precipitation. Moreover, organic acids, dimethyl sulfide, and nitrogen compounds released during the decomposition of plants and animals, though weakly acidic, may also participate in acid rain formation under specific environmental conditions.

1.3. Emission status of acidic pollutants and conditions for their transformation

The severity of sulfur dioxide (SO₂) pollution is closely related to the concentration of sulfate ions and the pH level in precipitation. Generally, in areas with more severe SO₂ pollution, there is a negative correlation between the pH value and the concentration of sulfate ions in rainfall. For example, in some industrially developed regions, the extensive combustion of coal and other fuels results in large-scale SO₂ emissions, which significantly increase the acidity of precipitation in those areas.

1.4. The acidity of particulate matter and its buffering capacity

Particulate matter in the atmosphere plays a dual role in the formation of acid rain. On the one hand, catalytic metals contained in these particles can promote the oxidation of SO₂ into various acids, thereby increasing the likelihood of acid rain formation [2]. On the other hand, particulate matter is also capable of neutralizing acids through chemical reactions. However, when such particles exhibit acidity even in the absence of any external conditions, they themselves become a major source of acid rain. For example, some industrial emissions contain acidic particulate matter, which can participate in the acid rain formation process through atmospheric transport.

2. The impact of acid rain on crops

2.1. Acceleration of soil acidification

Although most soils in northern China are alkaline and possess a certain buffering capacity against acid rain, the situation is markedly different in southern regions, where soils are generally acidic. Under prolonged exposure to acid rain, the acidification problem in these southern soils becomes increasingly severe. These soils often contain high levels of aluminum hydroxides and other aluminum-bearing compounds. Under acidic conditions, the weathering rate of aluminum-containing minerals increases significantly, leading to the release of large amounts of aluminum ions. These ions can further form aluminum compounds that are absorbable by plants.

2.2. Alteration of soil microbial communities

2.2.1. Changes in bacterial growth

Acid rain has a significant impact on the growth of bacteria in soil. On the one hand, it inhibits the growth of individual bacterial species by altering the chemical properties and physical structure of the soil, thereby creating a harsher environment for microbial survival. For example, acid rain lowers soil pH, which affects enzyme activity and metabolic processes within bacterial cells, ultimately suppressing bacterial growth. On the other hand, acid rain also slows down the rate of bacterial reproduction. As nutrients are leached from the soil due to acid rain, the availability of essential substances for bacterial metabolism decreases, resulting in insufficient energy and material supply for reproduction and slower overall growth.

Microorganisms such as *Bacillus* and *Actinobacteria* play a vital role in the soil ecosystem by decomposing organic matter and proteins, thereby facilitating the beneficial cycling of nutrients. However, the onset of acid rain disrupts their living environment, inhibiting their growth and reproduction. For instance, the acidic components in acid rain may damage microbial cell structures and impair their metabolic functions. In addition, acid rain can alter the physical properties of soil, such as pH and moisture content, making it difficult for these microorganisms to adapt. The decline in their populations directly affects the decomposition of organic matter and proteins in the soil, hampers nutrient cycling, and ultimately leads to reduced agricultural productivity.

2.2.2. Decline in ammonification and nitrification

Acid rain leads to a reduction in the population of ammonifying and nitrogen-fixing bacteria in the soil, thereby diminishing the soil microorganisms' capacity for ammonification and nitrification. Ammonifying bacteria are responsible for converting organic nitrogen into ammonia, providing a source of nitrogen for plants. Nitrogen-fixing bacteria, on the other hand, convert atmospheric nitrogen into nitrogen compounds that plants can absorb and utilize. Both types of bacteria play a crucial role in the soil nitrogen cycle. Acid rain alters the soil's pH, creating unfavorable conditions for the survival and reproduction of these bacteria. For example, acidic soils may damage the enzymatic systems within these microorganisms, impairing their ability to carry out nitrogen transformations. The decline in microbial ammonification and nitrification reduces the availability of usable nitrogen in the soil, which negatively affects crop growth.

2.3. Direct damage to crop yields

Barley, cotton, soybeans, spinach, carrots, and chili peppers are among the crops that are particularly sensitive to environmental conditions and are easily harmed by acid rain. Take soybeans as an example: under the influence of acid rain, data indicate that in seven provinces in southern China, soybean yields were reduced by approximately 200,000 tons, resulting in an estimated annual economic loss of around 14 million yuan.

Crops such as kidney beans and peanuts are moderately sensitive to acid rain. While they can tolerate acid rain to some extent, prolonged exposure to acidic conditions may still result in poor growth and reduced yields.

Rice, maize, and similar crops are classified as acid rain-resistant. Although they possess a certain degree of resistance to acid rain, strong acid rain events can still cause significant damage and noticeable reductions in yield. On June 18, 1982, Chongqing, China, experienced a severe acid rain event with a pH as low as 3.9. During this event, over 666.67 hectares of rice leaves turned reddish within a short period, resulting in a loss of more than 400 tons of rice yield.

3. Cases of acid rain damage to crops

3.1. Acid rain damage caused by the Tonga volcanic eruption

3.1.1. Impact on crop growth

Following the eruption of the Tonga volcano, large quantities of nitrogen oxides and sulfur dioxide were released into the atmosphere. These gases reacted with atmospheric water and oxygen to produce acid rain. Tonga, located in the tropics, experiences a tropical climate, and the surrounding areas are susceptible to acid rain events. Acid rain has caused widespread damage to crops,

particularly affecting staple foods such as taro, maize, bananas, and garden vegetables, leading to significant reductions in their yields.

In regions like Tonga, the occurrence of acid rain alters the chemical properties of the soil. The soil ecosystem, originally stable, changes under the influence of acid rain, deteriorating the growth environment for crops. For example, aluminum ions in the soil are released at an accelerated rate due to acid rain, transforming into aluminum compounds that plants can absorb [3]. When plants absorb excessive amounts of aluminum over an extended period, toxic symptoms may develop, potentially leading to plant death. Additionally, acid rain accelerates the leaching of mineral nutrients from the soil, causing soil infertility and adversely affecting normal crop growth and development. Furthermore, acid rain can induce outbreaks of crop diseases and pests, contributing to yield reductions. Studies have shown that acid rain can reduce wheat yields by 13% to 34%, while crops such as soybeans and vegetables are also vulnerable, resulting in decreased protein content and overall production.

3.1.2. Fish mortality and its impact on fisheries

The impact of acid rain on marine environments is also significant. Acid rain can cause a rapid and substantial decrease in the pH of local water bodies. Fish rely heavily on stable aquatic environments for survival, and drastic changes can impair their respiratory functions. The harmful substances present in acid rain make it difficult for many fish to adapt to these sudden environmental changes, leading to mass fish mortality. This directly results in economic losses in fisheries, and the associated industrial chains face substantial challenges and crises.

3.2. Other cases of acid rain damage in different regions

Acid rain can cause severe corrosion to buildings and industrial equipment, resulting in substantial economic losses. For example, the strong corrosive nature of acid rain significantly accelerates the degradation of construction materials and structures. Historically valuable monuments, such as the Taj Mahal and the Leshan Giant Buddha, have suffered considerable damage due to acid rain corrosion. In the industrial sector, acid rain corrodes machinery and equipment, reducing their service life and increasing maintenance costs.

4. Research progress on the impact of acid rain on crops

4.1. Acidity and chemical composition of atmospheric precipitation in China

In southern China, the annual average pH value of atmospheric precipitation over large areas is below 4.5, with some regions recording even lower values. The main anions and cations in atmospheric precipitation in China are sulfate (SO_4^{2-}), calcium (Ca^{2+}), ammonium (NH_4^+), and nitrate (NO_3^-). These characteristics of precipitation acidity and chemical composition have exerted multifaceted impacts on agricultural production in China.

On one hand, the large quantities of sulfate (SO_4^{2-}) and nitrate (NO_3^-) ions enhance the acidity of precipitation, directly harming soil and crops. When this acidic precipitation falls onto the soil, it accelerates soil acidification, damages soil structure, and affects the availability of nutrients in the soil, thereby impeding the growth and development of crops.

On the other hand, calcium (Ca^{2+}) and ammonium (NH_4^+) ions can partially buffer the effects of acid rain. However, in regions severely affected by acid rain, this buffering capacity may gradually weaken [4]. With continuous acid rain leaching, calcium and ammonium ions in the soil are

progressively depleted, leading to a decline in soil buffering capacity, which further exacerbates soil acidification and its harmful impact on crops.

4.2. Effects of acid rain on crop growth and quality

Simulated acid rain spraying experiments have been conducted to study the effects of acid rain with different pH levels on crops. The results indicate that the extent of damage depends on the acidity (pH value), crop species, growth stage, and experimental environmental conditions.

During the seed germination stage, acid rain with low pH values inhibits both the germination rate and speed of seeds. For example, seeds of sensitive crops such as barley, cotton, and soybeans exhibit significantly reduced germination rates under highly acidic rain conditions. This is because acid rain damages the seed coat structure, impairs the absorption of water and nutrients, and may also suppress enzyme activity within the seeds, thereby hindering the germination process.

Acid rain also has a significant impact on crop quality. For example, acid rain can reduce the protein content of soybeans and affect the taste and nutritional value of vegetables. Additionally, acid rain negatively influences crop yields.

Furthermore, the impact of acid rain on crops is closely related to their growth stages and experimental environmental conditions. Sensitivity to acid rain may vary at different growth stages; for instance, crops are generally more vulnerable to acid rain damage during the seedling stage, while their tolerance tends to increase as they mature. Additionally, environmental factors such as soil type and climate conditions influence the severity of acid rain's effects. In regions with acidic soils, the harmful effects of acid rain are more pronounced, whereas in humid climates, the leaching effect of acid rain may be intensified, thereby exacerbating its impact on crops.

4.3. Mechanisms of acid rain damage to plants

The damage caused by acid rain to plants primarily arises from its complex mechanisms of action. First, acid rain damages the epidermal tissues of leaves and injures the aboveground parts of plants. Acidic substances in acid rain, such as sulfuric acid and nitric acid, can corrode the cell walls on the surfaces of leaves and stems, resulting in physical injury to the plants. This destruction of the external protective layer makes plants more susceptible to pathogen infection [5]. For example, in regions frequently affected by acid rain, crop leaves often exhibit damage and spotting, which are direct consequences of acid rain corrosion.

Secondly, acid rain causes soil acidification, which indirectly affects plants. Acid rain accelerates the leaching of mineral nutrients from the soil and alters soil structure, leading to soil degradation and infertility, thereby impairing plant growth and development. Essential nutrients such as potassium, sodium, calcium, and magnesium are leached away and carried into groundwater or rivers by rainwater. Over time, this continuous leaching results in a severe depletion of nutrient elements in the soil.

Moreover, acid rain affects soil microbial communities, which in turn impacts plant growth. It alters the structure of soil microbial populations, causing reductions in bacterial cell size and slower reproduction rates. Specifically, acid rain decreases the populations of key microbial groups responsible for decomposing organic matter and proteins—such as *Bacillus*, *Actinobacteria*, and related fungi—thereby disrupting the healthy cycling of nutrients in the soil and ultimately leading to reduced crop yields [6].

5. Conclusion

The damage caused by acid rain to crops is multifaceted, including the acceleration of soil acidification, alteration of soil microbial communities, and direct harm to crop growth. To mitigate the adverse effects of acid rain on agriculture, comprehensive measures must be implemented at multiple levels, including national policy, technology, agricultural production, and environmental management. At the same time, enhancing the monitoring and research of acid rain, and continuously exploring more effective prevention and control methods, is of great significance for protecting agricultural production and the ecological environment.

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