CHAPTER

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Factors and consequences of acid rain incidence

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ABSTRACT

In the mid-seventeenth century in England, at the epicenter of the Industrial Revolution, due to high air pollution, observations were initiated on rainfall with acid content that harmed ecosystems. With industrial advancement on a global scale, acid rain has become frequent in many parts of the world. Acid rain results from chemical reactions, mostly mediated by anthropogenic actions such as industrial activities that cause the emission of sulfur dioxide (SO2) and nitrogen oxide (NOx) into the atmosphere, and produce strong acids such as sulfuric acid (H 2SO4) and nitric acid (HNO3). These cause various damages to human health as well as damage to the air, in the aquatic environment, attacking the soils, agriculture, buildings, and monuments. There are several international and national instruments to regulate guidelines that prevent polluting activities and thus try to mitigate the negative effects of acid rain, the most recent being the Sustainable Development Orders (SDGs). Despite the existing policies, it is necessary to impose more on sustainable regiments and to encourage research on the subject so that, together, it acts more severely against the effects of acid rain around the world. This research presents the concept of acid rain, exposure to risk factors, consequences, and reflections on the challenges of managing acid rain.

Keywords: Acid particles, Nitric acid, Sulphuric acid, Damage to surfaces, Statues, Buildings.

1 INTRODUCTION

Rainwater plays a primary role in the biogeochemical balance of the entire biota through the redistribution and cycling of chemical elements, such as the transport and removal of elements across the earth's surface. From the negative action of the human being with the environment causing the emission of gases and chemical compounds aggressive to the atmospheric air, mediated by industries, burning of fuels, and smelting of metals, chemical reactions occur in the body of precipitation in the atmosphere generating acid rain harming both human health and ecosystems.

The first record of recognition and studies related to acid rain in the world were made in the mid-seventeenth century at the epicenter of the industrial revolution when by emission of gases expelled by the large chimneys of the industries was noted as a dense pollution of atmospheric air that modified the chemical composition of the precipitation and provided damage to the soil and plants of the region due to the formation of sulfuric acid (H_{2SO4}). Faced with this new environmental problem, over the centuries there have been studies directed on the subject and public policies, aiming at mitigating the effects mediated by acid rain. In this context, an interdisciplinary approach to acid rain is being presented, as well as its effects and consequences, in addition to bringing a reflection on the management and damages in the world related to Sustainable Development and the perspectives for the 2030 Agenda.

2 ACID RAIN: GENERAL DEFINITIONS

Rainwater plays an important role in balancing biogeochemical cycles, through the redistribution and cycling of chemical elements on the earth's surface, and interacting with various chemical and physical processes, such as transport and removal of elements (Martins et al., 2019).

Acid precipitation, or the more popular term "acid rain", is largely the result of chemical reactions in the atmosphere, facilitated by anthropogenic action for the most part, favored by the terrestrial burning of coal, and oil, smelting of metallic materials, use of vehicles, agricultural and industrial activities and emissions from thermal power plants, with emissions of sulfur dioxides (SO2) and nitrogen oxides (NOx1/4NOþNO2), producing strong acids such as sulfuric acid and nitric acid. Sulfur (S) and nitrogen (N) are the most important chemical components in the precipitation of the water cycle; when there are excessive inputs of Sulfur (S) and Nitrogen (N) in it, the buffer capacity of the water body can be reduced against the deposition of acids, thus accelerating the acidification of the water (ZHANG et al., 2024; LIKENS & BUTLER, 2017).

In smaller amounts, rainwater can also be polluted by natural sources, such as volcanic activities and biological processes of decomposition that run in the swamps and oceans. (FORNARO, 2006). In addition, natural rain is slightly acidic, having a pH of approximately 5.6, and does not present harm to living beings. However, acid rain has a pH between 4.2 and 4.4, and depending on its amount can interfere with the physiological processes of living beings and their metabolism (LIOTTA et al., 2021; TWAGIRAYEZU, 2023).

3 NEGATIVE REFLEXES

3.1 HUMAN HEALTH

Acid rain in human health does not result directly from acid deposition in soil or water but from the precursors of acid precipitation, SO2, and NO_x, which in addition to producing acidity, are gases that form particulates such as ammonium sulfate (NH4)2SO4) and ammonium nitrate (NO3NH4). These tiny particles are harmful to the lungs and can exacerbate asthma and other respiratory diseases. NO_x

is also a key component in the formation of ozone (O3), which is a severe lung irritant (LIKENS & BUTLER, 2018). Another study also notes that in a primary rocky environment in southwestern Sweden, it was observed that infants had diarrhea after consuming infant formula prepared in accumulated acidic well water, which dissolved copper from pipes and released heavy metals. Similar symptoms also affected adults who consumed acidic well water, presenting with long-term gastrointestinal symptoms, hip joint pain, fatigue, and a few years later fibromyalgia, with constant muscle aches throughout the body. This study is still one of the few that reports on acid rain and its effects on human health, which is surprising as it is known that acidity in rain directly and negatively influences nature, and humans are part of nature consuming its products (ROSBORG, 2020).

3.2 AQUATIC ENVIRONMENTS

Aquatic animals are also directly affected by acid rain, as large-scale fish species usually live between pH 6.0 and 9.0, but cannot withstand rapid chemical variation in their environment. When the ratio of $SO4^{2-}$ and $NO3^{-}$ in the water is altered by the acid, there may also be the dissolution of opaque heavy metals in the aquatic environment, which can further complicate the ongoing challenge of the stability of the marine ecosystem, affecting, for example, the decomposition of the biological materials of this ecosystem by aquatic fungi, the main decomposers of this medium. Not enough, acid deposition can mobilize aluminum from soils in watersheds, and the toxic form of aluminum can enter lakes, streams, and rivers in drainage waters. There are reports that high levels of dissolved aluminum (Al3) can damage the gills of fish and result in their mortality. Studies in the Adirondack Mountains of North America have shown that lakes with a pH below 5 may have only one or two species of fish, while lakes with a pH greater than 6 have on average five or more species of fish, and as a consequence of acidity, there may also be a decline in the species richness of zooplankton and other invertebrates that are an integral part of the aquatic food chain. As a general result of an acidified aquatic environment, there may be the collapse of the entire aquatic food web (LINKENS & BUTLER., 2018; Malik et al., 2020; DU et al., 2022; ZHANG et al., 2024).

Periods of melting in cold regions can also be worrisome. "Episodic acidification" in areas that have received acid deposition is a cause of high fish mortality. In climates with cold, snowy winters, there is an accumulation of snow during the winter, and when an initial period of snow melt occurs, many of the ions are leached from the compacted and concentrated snow layers, including toxic H+ and Al3+ from the soils. Thus, there is a pulse of acidity in surface waters during these early thaws, leading to large-scale mortality of acid-sensitive fish (LIKENS; Butler, 2018).

3.3 SOILS AND AGRICULTURE

As for the effects of acid rain on the soil, it is known that it decreases its pH, even if the soil has acid buffering capacity to reduce the pH variation, according to each type of soil and its history of land use. Soil characteristics such as cation exchange capacity, organic matter, and clay content significantly influence the buffering capacity of the soil, and affect the adsorption coefficient of cation ions of it, as well as the release of ions with acid rain, including exchangeable base cations and adsorbed heavy metals (IQ et al. 2022).

Despite the adaptation of different soil types, acid rain still has negative impacts on ecosystems Southern China, for example, is one of the three main regions of acid rain among terrestrial ecosystems, and the components of H+, $SO4^{2-}$ and $NO3^{-}$ have previously been reported as a precursor to increased aluminum dissolution and inducing a decline in soil fertility, as low pH can damage the shoots and roots of plants and result in decreased root biomass (WEI et al. 2021).

In addition, the relationship between soil respiration and microbial community structure is relevant for changes in the stability of the forest soil ecosystem and chemical cycling, which can be altered by acid rain, since the acidification caused by it can lead to variations in the soil substrate, such as reduction of organic carbon and reduction in enzymatic activities and changes in forest species composition (LI et al., 2021).

The acidity caused by rain can also exert harmful effects on the leaf, stem, and roots of plants, and may cause the reduction of the chlorophyll a/chlorophyll b ratio, the loss of biomass of trunks and roots, impair the transport of water within the plant and make some nutrients unavailable in the soil, hindering the development of the plant, and the intensity of the damage being independent of the stage of development and the physiological conditions of the same (ZHA et al., 2021; ZHANG Y. et al., 2023).

An example is soybeans, a common product of the food crop, which usually grows in regions where acid rain pollution usually occurs. It is an important food highly recommended for toxicological research by the United States Environmental Protection Agency (2012), since acid rain hinders the assimilation of nitrogen in the roots of seedlings of this product, indirectly impacting the health of those who consume this food (ZHANG F. et al., 2017).

3.4 BUILDINGS AND MONUMENTS

Industrialization and constant development in the major global urban axes lead to serious problems of environmental pollution, including potentiating the occurrence of acid rain. A given event causes economic losses of great proportions by corrosion to the products of civil engineering with a great focus on the deterioration of the rocky surfaces of several buildings, modern or historical, and on monuments that are the cultural heritage of society (GAO, 2021; YU, 2021; RODRIGUEZ, 2023).

The calcium carbonates constituents of the hydrated cement paste that are part of the buildings and monuments, in addition to suffering wear by the natural weather and with the advance of its useful life, have their surface wear more aggressively with the acid rain factor. This is often presented with sulfur dioxide (SO2), sulfur trioxide (SO3), nitric acid (HNO3), and even sulfuric acid (H2SO4), which react with the silicates present in the structure and corrode from the outside in. There are great examples of iconic world heritage sites damaged by the effects of acid rain, they are the Taj Mahal in India and the Statue of Liberty in New York in the United States of America (FATIMA et al., 2020; GAO, 2021).

Given this, the main product of civil engineering attacked and that leads us to a greater concern is concrete. With the reaction between the precipitation acids together with the alkaline compounds of the concrete, the composition of the cementite is changed, promoting crystallization in which the material will expand and crack, thus causing a loss of strength. This brings great concerns because the concrete in a building has a structural supporting role. Therefore, aiming at greater safety of concrete and buildings in an environment that contains corrosive events from acid rain, it is essential to judge the design characteristics of concrete within its useful life (FATIMA et al., 2020; GAO, 2021; YU, 2021; GONCALVES, 2022).

In another area of civil construction in a more ornamental aspect, it also fits the cultural heritage conceived in carbonate rocks. Monuments that in their composition stand out the limestone and marble for example. These also suffer markedly from the corrosive effects of acid rain, since they present themselves with various porosity contents throughout their structure. These materials can react readily with acids and dissolve. Not enough, when there is the direct dissolution of materials such as limestone and marble, sulfur dioxide (SO2), the precursor of acid rain, can react directly with limestone in the presence of water and form gypsum (CaSO4), which will detach from the limestone and be washed away by rainwater. Therefore, there is a potentiation of damage to monuments that are in extremely aggressive environments due to acid deposition that results in the chemical dissolution of their structural composition. That is why it is of paramount importance to emphasize the fight against acid rain so that the preservation of these historical monuments is enhanced by individuals or organizations (HOYT, 2020).

4 HISTORICAL AND POLITICAL CONCEPTS ABOUT ACID RAIN

The growing industrial revolution in the mid-seventeenth century was noted in France and England, with anomalies, and records of damage to human health and biota due to the constant emissions of industrial gases. In 1845, Ducros was the first scientist to gain recognition of the phenomenon now known as acid rain. However, the scholar who named the acid rain event was an English chemist, Robert Angus Smith, from the first systematic atmospheric monitoring observing air pollution in England. And before the rainfall of the region with dense atmospheric pollution, damage to plants and materials was noted due to sulfuric acid. The precipitation presented a chemical identity directly influenced by the combustion of coal, the region disposed near the sea, the wind regime, the decomposition of organic matter, and the rainfall regime accentuated in vast levels of frequency and quantity. From this in 1872, Smith published the book *Air and Rain: The Beginnings of Chemical Climatology*, which was an icon work of this strand of study providing a theoretical basis for successor scientists of the theme (FORNARO, 2006).

Faced with this phenomenon seen and qualified at the epicenter of the industrial revolution, they began to notice in several countries such as Brazil, Canada, and Sweden occurrences of acid rain in the early twentieth century, as shown in Table 1. Initially, the records point to cases in Sweden, and from this, in 1948, the country was the scene of the first rainwater monitoring network in Europe coordinated by Hans Egner. Sweden suffered a lot in the 60s and 70s due to the emissions of nitric oxide and sulfur dioxide that were incorporated in precipitation and caused acidity in rainfall. On the other side of the Ocean, in North America, basically in the same period, this event was noticed in Canada when they interrelated the deposition of sulfates and other chemical compounds with atmospheric air pollution near metal smelting sites. Given this, the Canadian ecologist Eville Gorham developed studies aimed at understanding the effects of acid precipitation on ecosystems. And later this environmental anomaly was seen in the Asian continent (FORNARO, 2006; FATIMA et al., 2020). In Brazil, the consequences caused by acid rain happened through the emission of carbon dioxide with fuel oil containing sulfur used in factories to heat boilers. Today, the path to sustainability favors the fight against air pollution using some resources such as electricity or gas, which do not pollute as much. However, there are still factories that use coal as a source of energy because of their financial condition, thus further damaging the atmospheric air (ATLAS, 1996).

With the evolution of acid rain cases around the globe, events were created for the applied explanation of acid rain, its effects, and consequences, proposing discussions for the mitigation, control, and reversal of this anomalous phenomenon from atmospheric pollution. These events were milestones, for example in 1972, in Europe, there was a conference proposing discussions on environmental issues and human health, where he inaugurated the exhibition of acid rain as a serious problem; In 1974, in the United States of America, following the Svante Oden Conferences in several universities in the country, the creation of the *National Atmospheric Deposition Program was proposed and encouraged*.

Soon after in 1975, there was the first symposium on the acidic issues of the forest ecosystem, to evaluate acidity and focus ecological attention around the world. From then on, there was a concentration on global environmental issues, proposing a conference every five years in various places around the world.

2005 at the 7th Acid Rain Conference, was marked by the advancement of the study on acid rain, because there was an interrelationship with other topics such as the formation of photochemical smog in large urban centers, changes in land use (destruction of forests) and preservation of biodiversity and human health, contributing worldwide to atmospheric preservation. It should also be noted that in 1993, Kowalock contributed to the development of knowledge of the acid rain phenomenon by discussing multidisciplinary issues about air pollution (FORNARO, 2006), as shown in Table 1.

Table 1 – Records, studies, and important events on acid rain

Locality	Period	Chaves Records
Indefinite	1845	The scientist Ducros identifies the phenomenon of acid rain.
England	1872	Robert Angus Smith, an English chemist, defines the phenomenon of acid rain from England's first atmospheric monitoring method, publishing this discovery in Air and Rain: The Beginnings of Chemical Climatology.
Sweden	1948	Europe's first rainwater monitoring network was coordinated by Hans Egner.
Canada	1950	Eville Gorham, Ecologist and Ph.D. in Botany, developed detailed research in the knowledge of the causes and effects of acid precipitation on ecosystems from interrelating in the country the deposition of sufacts with air pollution near metal smelting localities.
Sweden	1967	First complete theory about acid rain.
Sweden	1970's	In the decade the country suffers a lot because of the exacerbated emissions of Nitric Oxide and Sulfur Dioxide incorporated in the precipitations.
Brazil	1970's	The first records of acid rain occurrences in the South and Southeast regions of the country are noted.
Europe	1972	A conference addressing discussions on serious environmental issues and their effects on human health, where acid rain debuted as a serious environmental problem worldwide.
USA	1974	Svante Oden's lectures at various universities in the country addressing the theme and key report of the New York Times "The Poison that Falls from the Sky" mobilized the authorities against the phenomenon,
USA	1975	Acid Rain Conference, the first Symposium related to the theme.
USA	1982	Publication of a key article by Cowling: "Acid Precipitation in Historical Perspective".
Czech Republic	2005	In the 7th edition of the Acid Raind Conference, advances were made in the studies on acid rain, this time comprehensively interrelating other topics such as changes in land use, preservation of biodiversity, and formation of photochemical smog.

World	2010's	Increased emissions of Sulphur dioxide (SO2) and Nitrogen oxide (NOx) into the atmosphere from highly industrialized countries such as the USA, China, and part of Europe.

Source: Authors, 2023.

5 DAMAGE MANAGEMENT TOOLS

Through the consequences caused by acid rain, there are interventions applied to damage management and policies around the world against acid rain, as we can see in Table 2. There was in the United States, for example, the *Acid Rain Program*, a program that, by attributing damage caused by the emission of sulfur dioxide (SO2) and Nitrogen Oxides (NO_x) that are the main gases present in the acidity of rainwater, benefiting environmental causes and human health. The laws then combat air pollution governed by the *Clean Air Act*, a regulation that aims to reduce large tons of sulfur dioxide, as well as promote the encouragement of energy efficiency. To obtain this reduction, it is necessary to follow two restrictions, the first which is the reduction of fossil fuel and the second that of combustion in boilers of electricity generating plants, starting in the mid-twentieth century and adhering to the present day (BRENA, 2009).

On the other hand, in Brazil, each state has its laws to combat and reduce gaseous emissions present in various industries to reduce acid rain. According to Rodrigues et. al. (2021) after the Stockholm conference Brazil decreed some laws governing the protection of the environment, which are: Law No. 6,938, of August 31, 1981, which portrays the National Environmental Policy being the first to deal with environmental issues regulated by the Stockholm Convention, in 1988 with the new Federal Constitution providing a great step for environmental protection, attributing a complete chapter (article 225) the right to an ecologically balanced environment, as well as in paragraph 3 of the same article the sanction of criminal and admirative proceedings against the environment, whether for public or private companies and also Law No. 7,735, of February 22, 1989, which manifests the elaboration of the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) with the function of protecting and guaranteeing the quality of the environment.

In addition, there is also a defense instrument for sustainable construction, which was conceived by the UN high summit and called the 2030 Agenda where it proposes good practices policies in an interdisciplinary way to minimize the negative impacts of the present day both related to the fight against anomalous occurrences in agriculture, in the terrible infrastructure of the cities and communities of the world, the lack of environmental sustainability and global social inequality, for example. This 2030 Agenda encompasses objectives, seen in Table 2, to be met for a significant improvement in the quality of life of the entire world population.

These guidelines for the development of good practices are called the Sustainable Development Goals, the so-called SDGs. The main one in action and closely linked to the fight against the effects of acid rain, although it is not explicitly mentioned in the reports and does not have a guideline regarding the ozone layer, is SDG11, which is called Sustainable Cities and Communities (Table 3). Widely used for the protection and control of the levels of pollution that happens in the atmosphere and for proposing ways to combat this type of precipitation (LOBATO AND PIERRE, 2013).

Table 2 – Management interventions against acid rain

Instrument	Implementation period	Acting	State	General Objective
Acid Rain Program	1995	National	USA	Establish permanent limits for the total amounts of emissions of Sulfur Dioxides (SO2) and Nitrogen Oxides (NOx) from the burning of fossil fuels and combustion in boilers of electricity generating plants by the electric generation units of the United States, given the damages caused by the emissions of these pollutants. Governed by the Air Clean Act.
Law No. 6,938: Portrays the National Environmental Policy on the Environment	August 31, 1981	National	Brazil	According to Law 6,938 itself: "Preservation, improvement, and recovery of the environmental quality conducive to life, aiming to ensure, in the country, conditions of socioeconomic development, the interests of national security and the protection of the dignity of human life."
Law No. 7,735: Provides for the extinction of an agency and municipal entity, creates the Brazilian Institute of the Environment and Renewable Natural Resources, and provides other measures	February 22, 1989	National	Brazil	According to Law 7,735 itself: "to carry out actions of national environmental policies, referring to federal attributions, related to environmental licensing, environmental quality control, authorization of use of natural resources and environmental inspection, monitoring and control, in compliance with the guidelines issued by the Ministry of the Environment."
2030 Agenda: Sustainable Development Goals	2015	International	-	Achieve by 2030 a better world for all peoples and nations through public policies of good practices that result, in an interdisciplinary way, in environmental sustainability in excellence, in the extinction of global social inequality, in the improvement of the infrastructure of cities, and the accessibility of basic human resources.

Source: Authors, 2023.

In this way, we can highlight a very significant growth in sustainable practice, being applied in all areas of knowledge and attributing a perspective on the economic factor very strong, through this, companies are more proactive with the environmental cause adding in their projects as a way of cleaner production (TODOROV et al., 2014).

Table 3 – Sustainable Development orders

Objective	Proposal
1	End poverty in all its forms, everywhere
2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
3	Ensure healthy living and promote well-being for all, at all ages
4	Ensure inclusive and equitable quality education, and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure the availability and sustainable management of water and sanitation for all
7	Ensure reliable, sustainable, modern and affordable access to energy for all
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9	Building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation
10	Reduce inequality within and between countries
11	Making cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable production and consumption patterns
13	Taking urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

Source: Adapted Rodrigues *et al.*, 2021.

6 TECHNOLOGICAL INNOVATIONS TO COMBAT THE EFFECTS OF ACID RAIN

The growing evolution of technological innovations has been influencing the economic and sustainable growth of several countries, being directly linked to the individual's ability to create innovative technologies. It is a complex area, still existing lag for the handling of advanced technologies through various situations, such as the lack of training, infrastructure and even qualified professionals, which can lead to the evolution of problems in critical sectors and with considerable potential to contribute to the development of sustainable solutions (PINSKY AND KRUGLIANSKAS, 2017). As good examples, we have projects focused on ecological cement binders, which have low carbon materials in their composition and low cost. Among these, the cement based on magnesia (MgO), besides being ecological, is resistant to acid erosion and the sulfate of acid rain. In addition, recent developments in self-repairing cementitious materials suggest potential for durable and resilient cement-soil systems, with the presence of microcapsules incorporated into cement that release healing agents when requested. In addition, some stabilizing agents of this innovative cement can improve the health of the soil by helping in its structure, adding nutrients (N, P, and K), attenuating the acidification caused by mineral fertilizers, and increasing the water retention capacity; not enough, cementitious stabilization materials can also incorporate controlled-release reagents/microorganisms for better long-term remediation of structures (SHEN et al., 2019). Green roofs, present a solution to increase the sustainability and energy conservation of buildings, and produce several benefits for urban areas in social, economic, and environmental terms, in addition to reducing greenhouse gas emissions and the urban heat island effect. With the reduction of gas emissions, there is the possibility of reducing acid rain, improving air quality, producing more oxygen, sequestering carbon dioxide, and minimizing noise pollution in urban areas (CASCONE, 2019).

7 FINAL CONSIDERATIONS

Acid rain inserted in the daily life of society and increasingly present in the various global ecosystems causes severe damage to all human beings and means in direct or indirect contact, through toxicity and corrosiveness. Although there are political management instruments aimed at mitigating and extinguishing this undesirable phenomenon, such as international guidelines and Agenda 21, there is still a need for a greater imposition of the world councils in their sustainable regulations, in addition to the broad incentive to research on the subject so that, together, it acts more severely against anthropogenic actions and the effects of acid rain in the world.

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