Jurnal Fisika 16 (1) (2026) 09-16

Jurnal Fisika

https://journal.unnes.ac.id/nju/index.php/jf/index

Analysis of Rainwater Acidity Levels in Semarang City

Sri Wulan Siti Khotijah[1,3], Sri Endah Ardhi Ningrum Abdullah[1,2,*], Abdul Latif [1,2], Sunarno[1], Dwi Atmoko[3]

[1]Master of Physics Study Program, Faculty of Mathematics and Science, Semarang State University, Semarang City
[2]Climatology Station, Meteorology, Climatology and Geophysics Agency, Semarang City
[3]Meteorological Climatological and Geophysical Agency, Jakarta, Indonesia

Article Info

Article History:

Received:
31 July 2024

Accepted:
9 December 2025

Published:
15 May 2026

Keywords:
Acid Rain, Rainwater, Chemical Compound, Semarang, Air Pollutants

Abstract

This study aims to analyze the acidity level and chemical composition of rainwater in Semarang city during the period 2016-2023 to provide an understanding of the dynamics of rainwater in coastal-urban areas. Rainwater samples were collected by the BMKG climatology station and analyzed to determine the pH and concentration of major ions (SO42-, NO3-, Cl-, Na+, K+, Ca2+) descriptively. The results show that Semarang experiences persistent acid rain events, with the highest frequency reaching 83,3% in 2020, and most rain events are the acid rain category (pH 3-5,5), while ideal and very good rain is only around 20-28% per year. The chemical composition of rainwater is dominated by strong acid ions, namely SO42-, NO3-, and Cl-, with a total contribution of 62,4%, while base ions (Na+, K+, Ca2+) only provide limited neutralization capacity. Variations in pH and ion concentrations follow seasonal monsoon patterns and are influenced by the interaction between anthropogenic emissions and marine aerosols, reflecting the mixed marine-urban character of the atmosphere. These findings provide an important scientific basis for air quality monitoring and future studies of atmospheric chemistry in urban coastal areas

✉ Correspondence address:
Climatology Station, Meteorology, Climatology and Geophysics Agency, Semarang City
E-mail: sriendah.ardhiningrum@bmkg.go.id

p-ISSN 2088-1509

INTRODUCTION

Atmospheric precipitation is a crucial component of the hydrological system. It also acts as a medium for cleaning various gases and aerosols in the atmosphere. During cloud and rain formation, water vapor dissolves gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other dissolved particles. The dissolution of CO_2 produces weak carbonic acid, resulting in a normal rain pH of around 5,6 (Fisher, 2017; Josh, 2025). When rainwater has a pH <5,6, this condition is categorized as acid rain (Alfiandy et al., 2021; Budiwati, 2009) and is generally caused by the formation of sulfuric acid (H_2SO_4) and nitric acid (HNO_3) through the oxidation of SO_2 and NO_x in the atmosphere (Figure 1) (Si & Li, 2024; Wondyfraw, 2014).

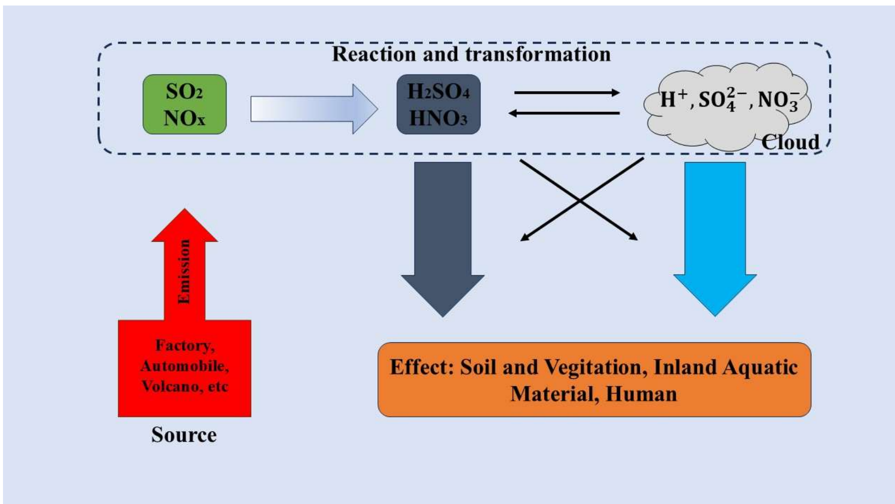


Figure 1. A flow chart showing the formation of acid rain and its interaction with the environment (Wondyfraw, 2014)

Acid rain is a global environmental issue due to its impacts on soil quality, aquatic ecosystems, material corrosion, infrastructure, and human health (ai citraningsih, 2015). Recent studies have shown that rainwater with high sulfate and nitrate ion content can increase the mobilization of heavy metals, affect soil acidity, and accelerate material degradation in urban areas (Zhang et al., 2024). Globally, rainfall chemistry trends are strongly influenced by the intensity of anthropogenic activities such as transportation, industry, and urbanization processes (Keresztesi et al., 2020; Si & Li, 2024).

Semarang City has unique atmospheric characteristics as a coastal city, a center of industrial activity, and a transportation hub. This area is traversed by a major logistics route, the Pantura route, which accommodates thousands of heavy vehicles daily. It also houses the Candi industrial area, Tanjung Emas Port activities, and Ahmad Yani Airport. These conditions make Semarang vulnerable to the accumulation of air pollutants SO_2, NO_x, and particulates, which can then contribute to the formation of acid rain. Furthermore, as a coastal city, Semarang is affected by marine aerosols that carry CL^- and Na^+ ions, forming a "mixed marine urban" rain chemical pattern also found in large coastal cities such as Shenzhen and Fuzhou, China (Huang et al., 2024; Zeng et al., 2024).

Various studies have been conducted in Indonesia on rainwater chemistry, such as studies in Palu (Alfiandy et al., 2021) and Pontianak (Katulistiyani et al., 2015). However, these studies focused on relatively short observation periods and did not integrate long-term ion composition analysis in coastal-urban areas such as Semarang. However, comprehensive studies of pH and major ion variations (SO_4^{2-}, NO_3^-, Na^+, K^+, and Ca^{2+}) over long timescales are crucial for understanding the dynamics of pollutant sources and long-term changes in atmospheric conditions. Recent studies indicate that multi-year analyses are necessary to detect deposition patterns due to urbanization, meteorological variability, and changes in emission patterns (Huang et al., 2024; Rathore et al., 2025).

The absence of long-term studies on the acidity level and chemical composition of rainwater in Semarang city serves as a scientific basis for understanding the intensity of acid rain, dominant ion patterns, and potential sources of pollutants in coastal-urban areas of Indonesia. Therefore, this study aims to analyze the acidity level of rainwater in Semarang city during the period 2016-2023, identifying the main chemical composition of rainwater, namely the role of strong acid ions and basic ions. This study provides long-term baseline data on acid rain in coastal areas as well as scientific contributions in monitoring atmospheric quality and emission control.

METHOD

The location of data collection is at the Central Java Climatology Station, which is located at -6° 59' 5.0022" LU, and 110° 22' 52.3122" BT. The location of data collection is in a good location with the environment to the west and southwest, approximately 4 km away is the Industrial area, on the south side is the main Pantura road, to the north is Ahmad Yani airport and the north coast of java and to the east is the urban area of Semarang city.

The data used in this study are primary data obtained from rainwater sampling in the station's tool park, conducted every Monday with a weekly period. This sampling is analyzed at the BMKG Air Quality Testing Laboratory, which then produces data in the form of rainwater pH data and standard weekly chemical compounds. Furthermore, the data is processed into monthly data for the period 2016-2023. This data is presented descriptively to determine the level of rainwater acidity according to the acid rain category. Meanwhile, the chemical compounds contained in rainwater are processed and adjusted according to the period of rain occurrence to describe the most dominant types of compounds that determine acid rain. Other chemical compounds are analyzed as base formers, both weak bases and strong bases.

RESULTS AND DISCUSSION

Rainwater Acidity Level

The criteria for rainwater acidity according to the Meteorology, Climatology, and Geophysics (BMKG) are classified into six categories. The alkaline pH category is when the rainwater pH value is more than 7. Perfect rainwater, tending to be neutral like surface water, has a pH ranging from 6,1 to 7. Ideal rainwater pH has a pH value ranging from 5,6 to 6. Meanwhile, the criteria for acid rain, high acid rain, and extreme acid rain are when the rainwater pH value ranges from 4,1 to 5,5; 3 to 4; and <3, respectively (Alfiandy et al., 2021). The level of rainwater acidity observed at the Central Java climatology station is shown in Figure 2. Between 2026 and 2023, acid rain events occurred almost throughout the year, varying in certain months of each year. Rainfall meeting excellent rainfall criteria occurred consecutively in May and June of 2017 and 2018, with other months varying across years. Compared with several regional studies, the frequency of acid rain in Semarang is relatively high. For example, rain chemistry studies in Palu and Pontianak reported more variable pH and a generally lower frequency of acid rain than observed in Semarang (Alfiandy et al., 2021; Katulistiyani et al., 2015). Semarang's position as a rapidly developing coastal city with dense transportation and industrial corridors further supports this interpretation.

Chemically, the decrease in rainwater pH is controlled by the formation of strong acids in the atmosphere. SO_2 and NO_x gases released from fossil fuel combustion undergo oxidation in the gas and liquid phases to form H_2SO_4 and HNO_3, which then dissociate to produce H^+ ions in raindrops

(Rathore et al., 2025; Si & Li, 2024; Wondyfraw, 2014).

$$SO_{2\,(g)} + H_2O_{\,(l)} \rightarrow H_2SO_{3\,(aq)}$$

$$H_2SO_{3\,(aq)} + \text{oxidant } (H_2O_2, O_3) \rightarrow H_2SO_{4\,(aq)}$$

$$NO_{2\,(g)} + OH^{\bullet} \rightarrow HNO_{3\,(aq)}$$

Global synthesis studies show that SO_4^{2-} and NO_3^- concentrations in rainwater tend to increase in areas with high anthropogenic emissions, while pH decreases (Keresztesi et al., 2020; Si & Li, 2024). This pattern is accompanied by a predominance of sulfate and nitrate ions in rainwater. Recent studies in other coastal cities, such as Shenzhen and Fuzhou in China, show that a combination of intensive urbanization and marine aerosol inputs produces a distinctive rainfall chemical pattern: relatively low pH, a predominance of SO_4^{2-} and NO_3^-, and significant contributions of Na^+ and Cl^- from the ocean (Huang et al., 2024; Zeng et al., 2024). These findings align with the characteristics of Semarang, which also exhibits a predominance of strong acid ions and the influence of marine aerosols (see figures 4 and 5). The high frequency of acid rain in Semarang can be understood as the result of a superposition between high local emissions and tropical coastal atmospheric dynamics that favor the formation of strong acids in clouds.

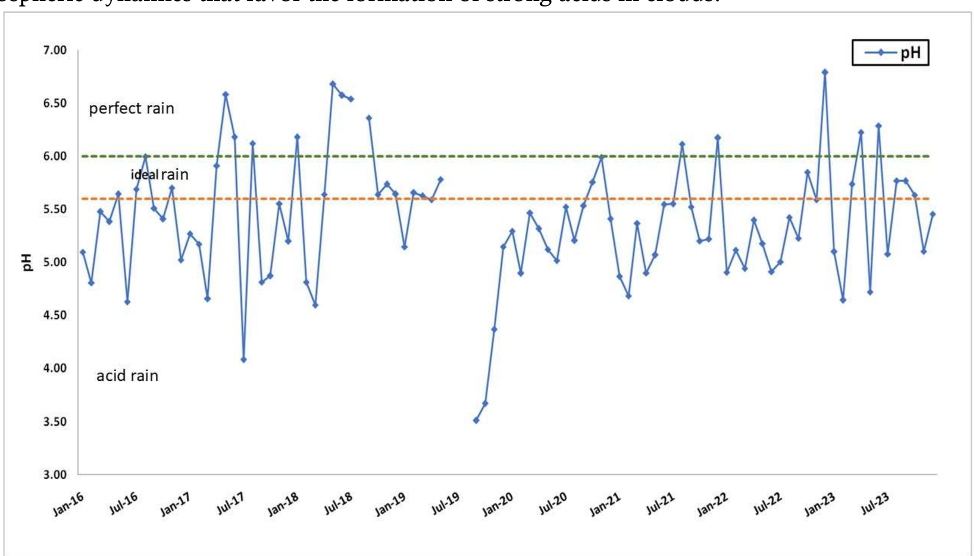
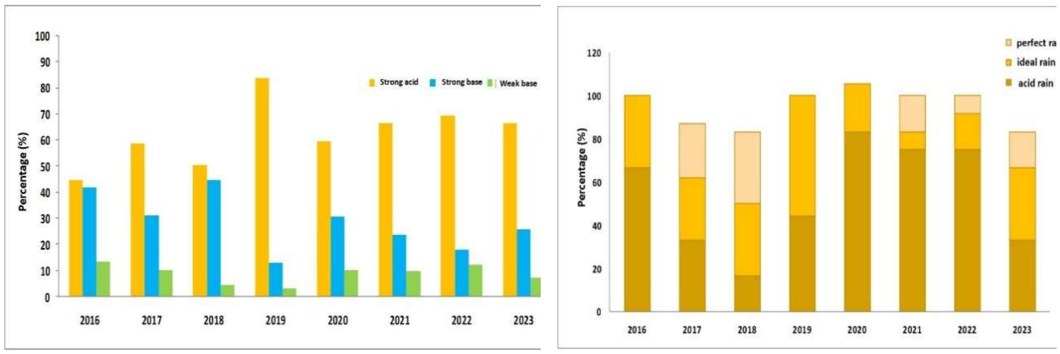


Figure 2. Rainwater acidity levels at the Semarang Climatology Station in 2016 - 2023

The frequency of rainfall events meeting acid rain criteria during the period January 2016–December 2023 was dominated by acid rain, with the highest percentage being 83,3% in 2020 (see Figure 3b). Meanwhile, rainfall that fell into the ideal rain category had the highest percentage of 55,6% in 2019, and perfect rain had the highest percentage of 33,3% in 2018.

The acidity of rainwater is influenced by the combination of the distribution of compounds that have acidity levels of strong acids, strong bases, and weak bases. Strong acids, when dissolved in water, will ionize completely to produce H^+, and the pH acidity value will be low. Strong bases, when dissolved in water, will ionize to produce hydroxide ions, OH^-. In contrast, weak bases, when dissolved in water, only partially ionize and produce a small amount of hydroxide. The reaction between acids and bases will form a neutralization reaction, but the reaction results are not always neutral. The acid-base properties of rainwater are influenced by the strength of the acids and bases that make it up.



(a) (b)

Figure 3. Percentage of rainwater acidity level: acidity distribution (a), acid rain occurrence (b)

The distribution of compounds contained in rainwater is shown in Figure 3a. Strong acid compounds have a percentage ranging from 47% - 83,7% in the last 8 years. The highest strong acid content was in 2019. On the other hand, the composition of strong base compounds in rainwater for eight years averaged 28,7%, with the lowest percentage being 13,3% in 2019 and increasing again four years later to an average 24,6%. Meanwhile, the composition of weak base compounds contained in rainwater has a fairly small percentage, namely an average of 8,9% with a range of 3,1% - 13,4%. this confirms that the content of strong acid compounds is the main component determining acid rain at the Semarang climatology station. The location of the climatology station, which is right on the edge of the Pantura of Java, also confirms that a large potential contributor to acid rain is vehicle exhaust emissions. This is as stated by Katulistiyani et al., (2015); Pohan, (2002) Exhaust emissions from diesel and petrol-fueled motor vehicles are the main contributors to acid rain, namely when sulfuric acid and sulfite acid dissolve in water vapor, which falls as rain.

Chemical Compounds of Rainwater

The chemical compounds in rainwater measured at the Semarang climatology station consist of two main compounds, namely strong acids and strong bases. Strong acid compounds consist of SO_4, NO_3, and Cl. Strong bases consist of K, Na, and Ca compounds. Figure 4 shows the distribution of compounds classified as strong acids contained in rainwater. In order, from high to low, the chemical compounds in rainwater are classified as strong acids, namely $SO_4 > NO_3 >$ Cl. According to ai citraningsih, (2015) The content of sulfate (SO_4) and nitrate (NO_3) is closely related to vehicle exhaust emissions. The increase in the number of vehicles in several cities in Indonesia is positively correlated with the increase in SO_x dan NO_x. As research conducted by Siswanto, (2012), states that the Pantura Road or Siliwangi Semarang road is the road with the highest traffic density volume, namely an average of 9233 PCU (passenger car unit) per day. SO_2 gas will be oxidized to SO_4^{2-}, and NO_3^- is oxidized to produce NO_x. long-term studies in India and other regions show that an increase in SO_4^{2-} in rainfall correlates with SO_2 emissions in urban-industrial areas. Similarly, NO_3^- increases with transportation intensity in multiple cities in Asia (Bhaskar et al., 2022; Rathore et al., 2025).

The highest SO_4 content was in July 2017 at 14,8 mg/l. Cl and NO_3, two compounds, were highest in September 2019 at 8,3 mg/l and 6.2 mg/l, respectively. This pattern aligns with findings in several other large cities, where SO_4^{2-} and NO_3^- are the main indicators of the contribution of industrial and transportation emissions, while Cl^- and Na^+ reflect the influence of marine aerosols in coastal areas (Huang et al., 2024; Latif et al., 2021; Zeng et al., 2024).

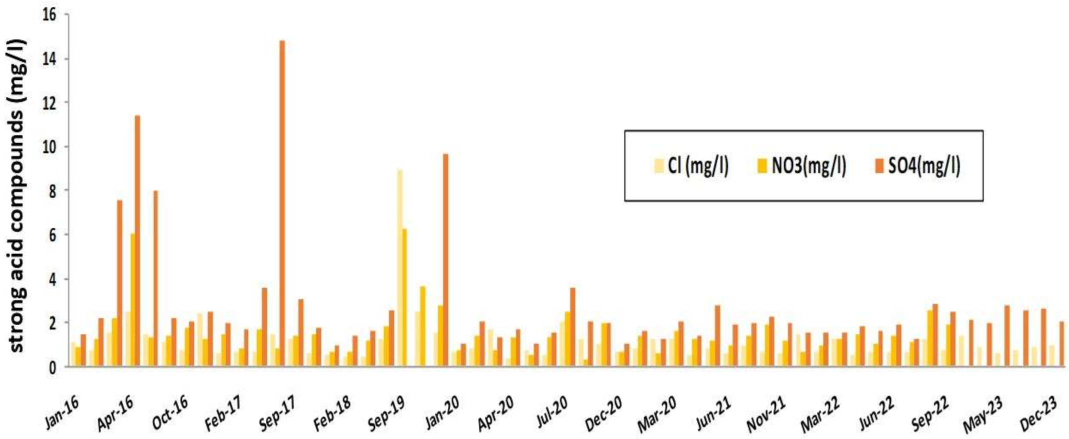


Figure 4. Composition of strong acids in rainwater at the Semarang Climatology Station

Figure 5 shows the distribution of compounds classified as strong bases contained in rainwater at the Semarang climatology station. Most of them are sodium and potassium compounds. The highest Na and K content occurred in June 2018 at 22,5 mg/l and in April 2016 at 23,3mg/l. Sodium compounds are salt compounds thought to originate from seawater during the evaporation process and condense into rainwater. Cl^- and Na^+ ions are characteristics of marine aerosols originating from fragments of sea salt particles carried by sea breezes. Zeng et al. (2024) showed that in large coastal cities such as Fuzhou, Cl^- and Na^+ can contribute >30% of the total ion composition of rainwater, while Ca^{2+} and K^+ ions come from soil dust, construction, and biomass burning. The role of soil cations as acid neutralizers was also reported by Si & Li (2024), who found that dry and dusty areas tend to have higher concentrations of base cations.

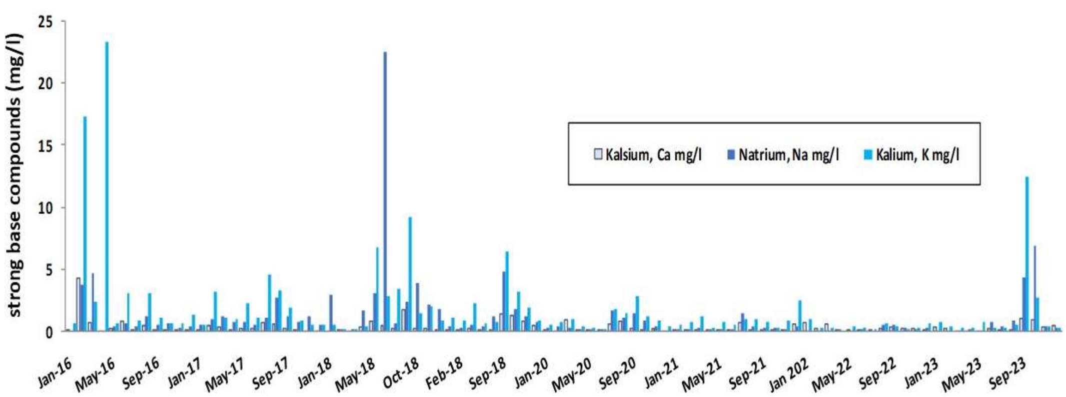


Figure 5. Composition of strong bases in rainwater at the Semarang Climatology Station

The SO_4^{2-} concentration reached its highest value in July 2017, and the NO_3^- and Cl^- concentrations peaked in September 2019. This pattern is similar to the characteristics of a tropical monsoon climate. In the dry season (June-September). Rainfall is lower, leaching processes are reduced, and ion concentrations in rainwater tend to increase. During the rainy season, rainfall volume is high, so ion concentrations decrease due to more efficient dilution and transport of pollutants. Studies in Shenzhen (Huang et al., 2024) and Varanasi (Rathore et al., 2025) reported a similar pattern, where ion concentrations and rain acidity exhibit strong seasonal fluctuations in response to variations in rainfall and pollutant sources.

The dominance of strong acid anions over basic cations indicates limited neutralizing capacity in the rainwater system in Semarang. Modern studies on neutralizing factors and non-marine fractions indicate that in many urban locations, Ca^{2-}, Mg^{2+}, and NH_4^+ play a significant role in neutralizing acidity caused by SO_4^{2-} and NO_3^- (Singh et al., 2024). However, when the total cations are smaller than the total anions, the pH remains low despite some neutralizing contribution. Results in Semarang confirm a similar pattern: the presence of Na^+, K^+, and Ca^{2+} is insufficient to offset the dominance of SO_4^{2-}, NO_3^-, and Cl^-, thus acid rain remains a common condition. This condition is in line with global assessments that in densely populated anthropogenic areas, rainwater tends to show a decreasing neutralizing capacity as acid emissions dominate (Si & Li, 2024; Zhang et al., 2024). This pattern is also similar to other large coastal cities reported in contemporary studies (Huang et al., 2024; Latif et al., 2021; Zeng et al., 2024) and strengthens Semarang's position as an important example of rainfall chemistry in urban-coastal Southeast Asia.

CONCLUSION

This study shows that rainwater in Semarang city during 2016-2023 consistently falls into the acid rain category, with the highest frequency reaching 83,3% in 2020. This dominance of acid rain indicates high exposure to acid precursors, especially SO_2 and NO_x from urban-industrial activities. The chemical composition of rainwater is dominated by strong acid ions (SO_4^{2-}, NO_3^-, and Cl^-) with a total contribution of 62,4%, while basic ions (Na^+, K^+, Ca^{2+}) only provide limited neutralizing capacity and are unable to offset the accumulation of acidity. This pattern confirms that the chemical structure of rainwater is simultaneously influenced by anthropogenic emissions and marine aerosols. Seasonal variations and the dominance of these ions indicate that Semarang's atmosphere has a mixed marine-urban character, typical of tropical coastal cities. Overall, this study provides an overview of the acidity and chemical composition of rainwater in Semarang, as well as providing an important basis for air quality monitoring and further studies on pollutant sources and atmospheric chemical processes.

ACKNOWLEDGEMENT

BMKG Semarang City Climatology Station, Central Java, for the facilities provided.

REFERENCE

ai citraningsih, waluyo eko cahyono. (2015). Analisis klaster kandungan kimia air hujan di sebagian wilayah indonesia-citraningsih2015.pdf (pp. 14–19).

Alfiandy, S., Permana, D. S., Nugraha, M. S., & Aulia Putri, I. J. (2021). Analisis kimia dan kualitas air hujan di Kota Palu sebagai penyebab terjadinya hujan asam. Jurnal Riset Kimia, 12(1), 10–18. https://doi.org/10.25077/jrk.v12i1.368

Bhaskar, V. V., Safai, P. D., & Mukherjee, S. (2022). Hydrochemistry of atmospheric precipitation over an urban station in the peninsular India: Assessment of the long-term data. Atmospheric Pollution Research, 13(3), 101343. https://doi.org/10.1016/j.apr.2022.101343

Budiwati, T. (2009). Analisis Hujan Asam Dan Co2 Atmosfer. Prosiding Seminar Nasional Penelitian, Pendidikan Dan Penerapan MIPA, Fakultas MIPA, Universitas Negeri Yogyakarta, 16 Mei 2009, 276–281.

Fisher, M. R. (2017). Acid Rain. In Environmental Biology. https://openoregon.pressbooks.pub/envirobiology/chapter/10-3-acid-rain/

Huang, Y., Yang, J., Liu, C., Jing, R., & Lu, Q. (2024). Spatial and Temporal Variations in Rainwater Chemistry in a Rapid Urbanization Area of Shenzhen, China. Atmosphere, 15(12), 1536. https://doi.org/10.3390/atmos15121536

Josh, H. (2025). The Chemistry of Acid rain. In General Chemistry - An Atoms First Approach. https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_General_Chemistry_-_An_Atoms_First_Approach_(Halpern)/Unit_3%3A_Stoichiometry/Chapter_8%3A_Aqueous_Solutions/Chapter_8.08%3A_The_Chemistry_of_Acid_Rain

Katulistiyani, R., Ihwan, A., & Nurhasanah. (2015). Analisis terjadinya hujan asam di kota pontianak akibat emisi gas dari industri dan kendaraan. Prisma Fisika, III(01), 15–20.

Keresztesi, Á., Nita, I.-A., Boga, R., Birsan, M.-V., Bodor, Z., & Szép, R. (2020). Spatial and long-term analysis of rainwater chemistry over the conterminous United States. Environmental Research, 188, 109872. https://doi.org/10.1016/j.envres.2020.109872

Latif, M. T., Othman, M., & Hassan, H. (2021). Composition of rainwater and influences over different regions of the world. In Precipitation (pp. 69–83). Elsevier. https://doi.org/10.1016/B978-0-12-822699-5.00004-5

Pohan, N. (2002). Pencemaran Udara dan Hujan Asam. Jurnal Digital Library, 4(1), 4–6. http://library.usu.ac.id/download/ft/kimia-nurhasmawaty2.pdf

Rathore, S., Ram, K., Kumar, P., & Mondal, A. (2025). Chemical composition, source apportionment of rainwater, and its contribution to nutrient deposition at an urban site of the middle Indo-Gangetic Plain region. Atmospheric Pollution Research, 16(7), 102518. https://doi.org/10.1016/j.apr.2025.102518

Si, L., & Li, Z. (2024). Atmospheric precipitation chemistry and environmental significance in major anthropogenic regions globally. Science of The Total Environment, 926, 171830. https://doi.org/10.1016/j.scitotenv.2024.171830

Singh, Y., Katoch, A., Yadav, S., Dhakad, S., & Kulshrestha, U. C. (2024). Estimation of Non-Marine Fractions of Ions in Rainwater at Three Sites of Different Characteristics in Haryana State (India). Aerosol and Air Quality Research, 24(6), 230252. https://doi.org/10.4209/aaqr.230252

Siswanto, A. (2012). Kajian Tingkat Kemacetan Lalu Lintas pada Jaringan Jalan yang Menjadi Akses Masuk Kota Semarang. Geo-Image, 1(1), 82–88.

Wondyfraw, M. (2014). Mechanisms and Effects of Acid Rain on Environment. Journal of Earth Science & Climatic Change, 05(06). https://doi.org/10.4172/2157-7617.1000204

Zeng, J., Han, G., Wu, Q., Qu, R., Ma, Q., Chen, J., Mao, S., Ge, X., Wang, Z.-J., & Ma, Z. (2024). Significant influence of urban human activities and marine input on rainwater chemistry in a coastal large city, China. Water Research, 257, 121657. https://doi.org/10.1016/j.watres.2024.121657

Zhang, L., Wang, J., Wang, S., Wang, C., Yang, F., & Li, T. (2024). Chemical characteristics of long-term acid rain and its impact on lake water chemistry: A case study in Southwest China. Journal of Environmental Sciences, 138, 121–131. https://doi.org/10.1016/j.jes.2023.03.028