

THE CHEMISTRY OF ACID RAIN GRADE 10 AND UP READING



Sub Plan

Science
Applicability

Improve students'
literacy skills



Reading Comment



★★★★★ Extremely satisfied - Great resource to work on student reading comprehension and it tied into the topic I was teaching. My students have been struggling with reading and I've been incorporating more reading into my lessons. Thank you for the resource.



SCROLL
to take a look inside!

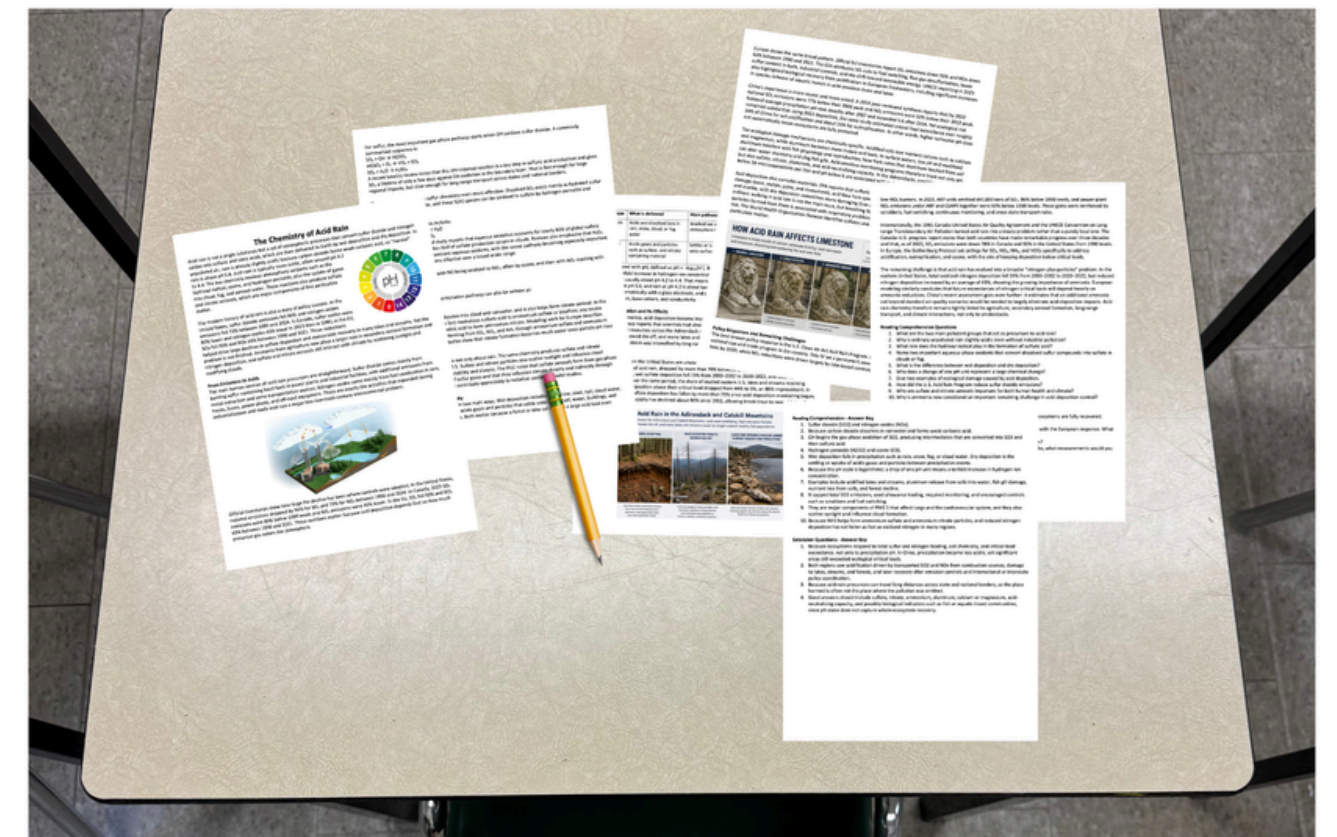


THE PROBLEMS YOU FACE

- **Limited time to teach scientific literacy and strengthen students' reading and analysis skills.**
- **Need meaningful extension activities to engage fast-moving learners.**
- **Difficulty creating effective last-minute sub plans that still support student learning.**

NO-PREP - PRINT/UPLOAD

- **CLASSROOM READY - No Prep, Ready-to-Use:** Print or assign digitally with Google Docs, Microsoft Word, and PDF formats for flexible classroom use
- **Questions and Answer Key**
- **Includes Varied Question Types:** Knowledge, thinking, connecting, application, and open-ended questions.



What Will Your Students Learn?

READING COMPREHENSION ARTICLE & QUESTION BUNDLE

Reading Comprehension Questions

1. What are the two main pollutant groups that act as precursors to acid rain?
2. Why is ordinary unpolluted rain slightly acidic even without industrial pollution?
3. What role does the hydroxyl radical play in the formation of sulfuric acid?
4. Name two important aqueous-phase oxidants that convert dissolved sulfur compounds into clouds or fog.
5. What is the difference between wet deposition and dry deposition?
6. What is the large chemical change?
7. G
8. H
9. V
10. V

Extension

- 1.
 - 2.
 - 3.
 - 4.
- The Chemistry of Acid Rain**
- Acid rain is not a single substance but a set of atmospheric processes that convert sulfur dioxide and nitrogen oxides into sulfuric and nitric acids, which are then delivered to Earth by wet deposition and dry deposition. In unpolluted air, rain is already slightly acidic because carbon dioxide forms weak carbonic acid, so "normal" rain is about pH 5.6. Acid rain is typically more acidic, often around pH 4.2. The key chemistry involves atmospheric oxidants such as the hydroxyl radical, ozone, and hydrogen peroxide, plus the uptake of gases into cloud, fog, and aerosol water. These reactions also produce sulfate and nitrate aerosols, which are major components of fine particulate matter.
- The modern history of acid rain is also a story of policy success. In the United States, sulfur dioxide emissions fell 94% and nitrogen oxides emissions fell 73% between 1990 and 2024. In Canada, sulfur oxides were 80% lower and nitrogen oxides 45% lower in 2023 than in 1990; in the EU, SO_x fell 93% and NO_x 63% between 1990 and 2021. Those reductions helped drive large declines in sulfate deposition and measurable recovery in many lakes and streams. Yet the problem is not finished. Ammonia from agriculture now plays a larger role in secondary aerosol formation and nitrogen deposition, and sulfate and nitrate aerosols still interact with climate by scattering sunlight and modifying clouds.
- From Emissions to Acids**
- The main human sources of acid-rain precursors are straightforward. Sulfur dioxide comes mostly from burning sulfur-containing fossil fuels in power plants and industrial facilities, with additional emissions from metal extraction and some transportation sources. Nitrogen oxides come mainly from fuel combustion in cars, trucks, buses, power plants, and off-road equipment. These are exactly the activities that expanded during industrialization and made acid rain a major late-twentieth-century environmental problem.

Article with Comprehension Questions

Grade 10 and Up

Print & Digital

- Sulfur dioxide and nitrogen oxides as acid-rain precursors
- Sulfuric acid and nitric acid formation
- Wet deposition and dry deposition
- pH and logarithmic acidity
- Sulfate and nitrate aerosols
- Lake, stream, and soil acidification
- Nutrient loss and aluminum toxicity
- Effects on ecosystems, fish, forests, and buildings
- The U.S. Acid Rain Program and international agreements
- Ammonia, particulate matter, and remaining environmental challenges

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Your Reading

The Chemistry of Acid Rain

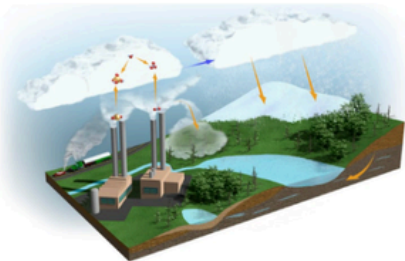
Acid rain is not a single substance but a set of atmospheric processes that convert sulfur dioxide and nitrogen oxides into sulfuric and nitric acids, which are then delivered to Earth by wet deposition and dry deposition. In unpolluted air, rain is already slightly acidic because carbon dioxide forms weak carbonic acid, so “normal” rain is about pH 5.6. Acid rain is typically more acidic, often around pH 4.2 to 4.4. The key chemistry involves atmospheric oxidants such as the hydroxyl radical, ozone, and hydrogen peroxide, plus the uptake of gases into cloud, fog, and aerosol water. These reactions also produce sulfate and nitrate aerosols, which are major components of fine particulate matter.



The modern history of acid rain is also a story of policy success. In the United States, sulfur dioxide emissions fell 94% and nitrogen oxides emissions fell 73% between 1990 and 2024. In Canada, sulfur oxides were 80% lower and nitrogen oxides 45% lower in 2023 than in 1990; in the EU, SO_x fell 93% and NO_x 63% between 1990 and 2021. Those reductions helped drive large declines in sulfate deposition and measurable recovery in many lakes and streams. Yet the problem is not finished. Ammonia from agriculture now plays a larger role in secondary aerosol formation and nitrogen deposition, and sulfate and nitrate aerosols still interact with climate by scattering sunlight and modifying clouds.

From Emissions to Acids

The main human sources of acid-rain precursors are straightforward. Sulfur dioxide comes mostly from burning sulfur-containing fossil fuels in power plants and industrial facilities, with additional emissions from metal extraction and some transportation sources. Nitrogen oxides come mainly from fuel combustion in cars, trucks, buses, power plants, and off-road equipment. These are exactly the activities that expanded during industrialization and made acid rain a major late-twentieth-century environmental problem.

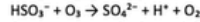
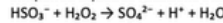


Official inventories show how large the decline has been where controls were adopted. In the United States, national emissions dropped by 94% for SO₂ and 73% for NO_x between 1990 and 2024. In Canada, 2023 SO_x emissions were 80% below 1990 levels and NO_x emissions were 45% lower. In the EU, SO_x fell 93% and NO_x 63% between 1990 and 2021. These numbers matter because acid deposition depends first on how much precursor gas enters the atmosphere.

For sulfur, the most important gas-phase pathway starts when OH oxidizes sulfur dioxide. A commonly summarized sequence is:
 $\text{SO}_2 + \text{OH} \rightarrow \text{HOSO}_2$
 $\text{HOSO}_2 + \text{O}_3 \rightarrow \text{HO}_2 + \text{SO}_3$
 $\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$
A recent kinetics review notes that this OH-initiated reaction is a key step in sulfuric acid production and gives SO₂ a lifetime of only a few days against OH oxidation in the boundary layer. That is fast enough for large regional impacts, but slow enough for long-range transport across states and national borders.

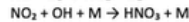
Cloud and fog water make sulfur chemistry even more effective. Dissolved SO₂ exists mainly as hydrated sulfur dioxide, bisulfite, and sulfite, and these S(IV) species can be oxidized to sulfate by hydrogen peroxide and ozone.

Simplified aqueous reactions include:

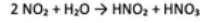


A recent atmospheric-model study reports that aqueous oxidation accounts for nearly 80% of global sulfate production and that more than half of sulfate production occurs in clouds. Reviews also emphasize that H₂O₂ and O₃ are the traditional dominant aqueous oxidants, with the ozone pathway becoming especially important as pH rises, while H₂O₂ remains effective over a broad acidic range.

Nitric acid chemistry begins with NO being oxidized to NO₂, often by ozone, and then with NO₂ reacting with OH:



A simplified aqueous disproportionation pathway can also be written as:



The nitric acid produced can dissolve into cloud and rainwater, and it also helps form nitrate aerosol. In the fine-particle system, ammonia first neutralizes sulfuric acid to ammonium sulfate or bisulfate; any excess ammonia can then react with nitric acid to form ammonium nitrate. Modeling work for Europe describes secondary inorganic PM_{2.5} as forming from SO_x, NO_x, and NH₃ through ammonium sulfate and ammonium nitrate, while aerosol-acidity studies show that nitrate formation becomes much easier once particle pH rises into an appropriate range.

This matters because acid rain is not only about rain. The same chemistry produces sulfate and nitrate aerosols that are inhalable PM_{2.5}. Sulfate and nitrate particles also scatter sunlight and influence cloud formation, so they affect both visibility and climate. The IPCC notes that sulfate aerosols form from gas-phase and aqueous-phase oxidation of sulfur gases and that they influence climate directly and indirectly through clouds; nitrate aerosols likewise contribute appreciably to radiative cooling in model studies.

Deposition and Measuring Acidity

Acidic material returns to Earth in two main ways. Wet deposition includes rain, snow, sleet, hail, cloud water, and fog. Dry deposition includes acidic gases and particles that settle onto leaves, soil, water, buildings, and monuments between rain events. Both matter because a forest or lake can receive a large acid load even when it is not raining.

Deposition type	What is delivered	Main pathway to the surface	Typical consequences
Wet deposition	Acids and dissolved ions in rain, snow, cloud, or fog water	Washed out of the atmosphere by precipitation	Acidifies lakes, streams, soils, and sensitive watersheds
Dry deposition	Acidic gases and particles such as sulfate- and nitrate-containing material	Settles or is absorbed directly onto surfaces	Damages leaves, soils, buildings, stone, and metals; can later be washed into water during storms

Acidity is measured with pH, defined as $\text{pH} = -\log_{10}[\text{H}^+]$. Because the pH scale is logarithmic, a drop of one pH unit means a tenfold increase in hydrogen-ion concentration. EPA notes that normal rain is about pH 5.6, while acid rain is usually about pH 4.2 to 4.4. That means rain at pH 4.6 is about ten times more acidic than unpolluted rain at pH 5.6, and rain at pH 4.2 is about twenty-five times more acidic. In practice, pH is measured electrometrically with a glass electrode, and precipitation-monitoring networks also analyze sulfate, nitrate, ammonium, base cations, and conductivity.

Historical Acidification and Its Effects

In eastern North America, acid deposition became impossible to ignore by the 1960s. New York’s environmental agency reports that scientists had already concluded by that decade that acid deposition was ravaging natural resources across the Adirondack and Catskill Mountains: soils were acidifying, high-elevation forests showed die-off, and many lakes and streams could no longer support healthy fish populations. The problem was intensified by long-range transport from upwind industrial regions in the Midwest.

Recovery data from the United States are unusually strong. EPA reports that wet sulfate deposition, a widely used indicator of acid rain, dropped by more than 70% between 1989–1991 and 2020–2022. Across the eastern United States, wet sulfate deposition fell 73% from 2000–2002 to 2020–2022, and total sulfur deposition fell 82%. Over the same period, the share of studied eastern U.S. lakes and streams receiving sulfur-plus-nitrogen deposition above their critical load dropped from 44% to 5%, an 88% improvement. In New York, statewide sulfate deposition has fallen by more than 75% since acid-deposition monitoring began, and Brooktrout Lake’s acidity has declined about 90% since 1992, allowing brook trout to reestablish self-sustaining populations.

Acid Rain in the Adirondack and Catskill Mountains

Across the Adirondack and Catskill Mountains, soils were acidifying, high-elevation forests showed die-off, and many lakes and streams could no longer support healthy fish populations.

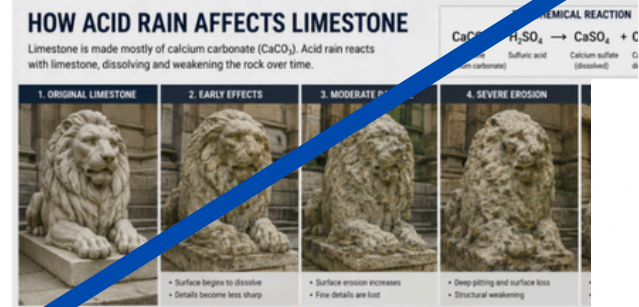


Europe shows the same broad pattern. Official EU inventories report SO_x emissions down 93% and NO_x 63% between 1990 and 2021. The EEA attributes SO_x cuts to fuel switching, flue-gas desulfurization, sulfur content in fuels, industrial controls, and the shift toward renewable energy. UNECE report also highlighted biological recovery from acidification in European freshwaters, including significant increases in species richness of aquatic insects in acid-sensitive rivers and lakes.

China’s experience is more recent and more mixed. A 2024 peer-reviewed synthesis reports that national SO₂ emissions were 77% below their 2006 peak and NO_x emissions were 32% below the 2006 level. National average precipitation pH rose steadily after 2007 and exceeded 5.6 after 2014. Yet ecological recovery remained substantial: using 2022 deposition, the same study estimated critical-load exceedance fell 14% of China for soil acidification and about 15% for eutrophication. In other words, higher rain not automatically mean ecosystems are fully protected.

The ecological damage mechanisms are chemically specific. Acidified soils lose nutrient cations and magnesium, while aluminum becomes more mobile and toxic. In surface waters, low pH and aluminum interfere with fish physiology and reproduction; New York notes that aluminum leach can alter water chemistry and clog fish gills. Acid-sensitive monitoring programs therefore track not only pH but also sulfate, nitrate, aluminum, and acid-neutralizing capacity. In the Adirondacks, conditions below 20 microequivalents per liter and pH below 6 are associated with reduced ecosystem resilience.

Acid deposition also corrodes materials. EPA reports that sulfuric and nitric acids in deposited precipitation damage stone, metals, paint, and monuments, and New York specifically notes corrosive effects on marble, with dry deposition sometimes more damaging than wet deposition. Human health impacts are indirect: walking in acid rain is not the main issue, but breathing SO₂, NO₂, and the fine sulfate and nitrate particles formed from them is associated with respiratory problems, asthma aggravation, and cancer risk. The World Health Organization likewise identifies sulfates and nitrates as major components of fine particulate matter.



Policy Responses and Remaining Challenges

The best-known policy response is the U.S. Clean Air Act Acid Rain Program. EPA describes the national cap-and-trade program in the country. Title IV set a permanent power-sector SO₂ emissions cap by 2010, while NO_x reductions were driven largely by rate-based controls and widespread installation of low-NO_x burners. In 2023, ARP units emitted 647,000 tons of SO₂, 96% below 1990 levels, and power-plant NO_x emissions under ARP and CSAPR together were 90% below 1990 levels. These gains were reinforced by scrubbers, fuel switching, continuous monitoring, and cross-state transport rules.

Internationally, the 1991 Canada–United States Air Quality Agreement and the UNECE Convention on Long-range Transboundary Air Pollution turned acid rain into a treaty problem rather than a purely local one. The Canada–U.S. progress report states that both countries have made remarkable progress over three decades and that, as of 2020, SO₂ emissions were down 78% in Canada and 92% in the United States from 1990 levels. In Europe, the Gothenburg Protocol set ceilings for SO₂, NO_x, NH₃, and VOCs specifically to address acidification, eutrophication, and ozone, with the aim of keeping deposition below critical loads.

The remaining challenge is that acid rain has evolved into a broader “nitrogen-plus-particles” problem. In the eastern United States, total oxidized nitrogen deposition fell 59% from 2000–2002 to 2020–2022, but reduced nitrogen deposition increased by an average of 43%, showing the growing importance of ammonia. European modeling similarly concludes that future exceedances of nitrogen critical loads will depend heavily on ammonia reductions. China’s recent assessment goes even further: it estimates that an additional ammonia cut beyond standard air-quality scenarios would be needed to largely eliminate acid-deposition impacts. Acid rain chemistry therefore remains tightly linked to agriculture, secondary aerosol formation, long-range transport, and climate interactions, not only to smokestacks.

Reading Comprehension Questions

1. What are the two main pollutant groups that act as precursors to acid rain?
2. Why is ordinary unpolluted rain slightly acidic even without industrial pollution?
3. What role does the hydroxyl radical play in the formation of sulfuric acid?
4. Name two important aqueous-phase oxidants that convert dissolved sulfur compounds into sulfate in clouds and fog.
5. Explain the difference between wet deposition and dry deposition?
6. Why does a change of one pH unit represent a large chemical change?
7. Give two examples of ecological damage caused by acid deposition.
8. How did the U.S. Acid Rain Program reduce sulfur dioxide emissions?
9. Why are sulfate and nitrate aerosols important for both human health and climate?
10. Why is ammonia now considered an important remaining challenge in acid-deposition control?

Extension Questions

1. The report argues that rising rainwater pH does not always mean ecosystems are fully recovered. Explain why, using China as an example.

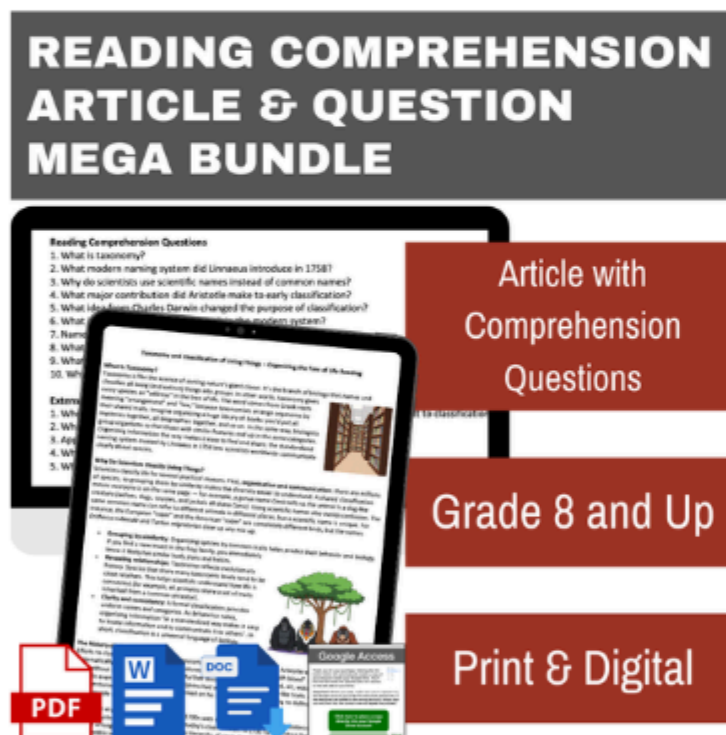
Full Answer Key

Comprehension and Extension Questions



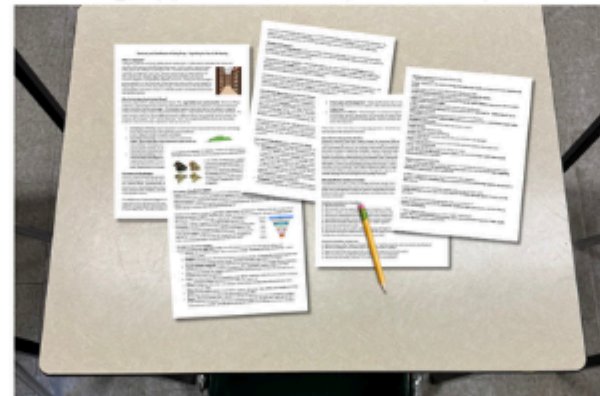
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- **Includes Varied Question Types:** Knowledge, thinking, connecting, application, and open-ended questions.



★★★★★ Extremely satisfied - It is a good supplemental activity either for review and at the same time introducing some concept. I also use this for sub plan. It is well presented, organized and interesting.

★★★★★ Extremely satisfied - This a great resource. I used this for a sub plan. It was fun and engaging for my students.

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