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Long-term Evolution of Pyrite Pollution and Its Cumulative Effects on the Environment

Zhouyuan Zhang

Shaanxi Agricultural Development Project Management Consulting Co., Ltd., Xi’an, Shaanxi, China

Abstract: Pyrite, as an important mineral resource, causes severe pollution during its exploitation and utilization, characterized by long-term persistence and complex cumulative environmental effects. This paper comprehensively reviews the process of pyrite pollution from its generation to long-term evolution and analyzes its cumulative impacts on environmental components such as soil, water, and atmosphere. The study reveals that pyrite pollution undergoes three stages: initial contamination, mid-term diffusion, and long-term accumulation and stabilization. These stages exert significant cumulative effects on various environmental elements, including soil acidification, heavy metal accumulation, water pollution, and atmospheric acid rain, severely damaging the structure and function of ecosystems. Although progress has been made in pollution control and mitigation, numerous challenges remain. The findings of this study hold significant importance for advancing research and governance of pyrite pollution, providing theoretical support and references for related efforts.

Keywords: Pyrite Pollution; Cumulative Environmental Impacts; Heavy Metal Speciation; Acid Mine Drainage; Ecosystem Resilience Thresholds.

1. Introduction

Pyrite is a critical mineral resource widely used in industries such as chemical engineering and metallurgy. However, its low exploitation efficiency and the generation of substantial waste residues, wastewater, and exhaust gases during mining, beneficiation, and smelting processes lead to severe environmental pollution. Pyrite pollution exhibits long-term persistence and complex cumulative environmental effects, damaging local ecosystems and potentially impacting broader regions (Fernández-Caliani et al., 2009; Romero et al., 2006) (Figure 1). Investigating the long-term evolution and cumulative environmental effects of pyrite pollution is crucial for ecological conservation, sustainable development of related industries, and regional sustainability. This paper aims to systematically outline the lifecycle of pyrite pollution, analyze its cumulative impacts on environmental components, and review existing research achievements and gaps. The study employs a literature review methodology, synthesizing extensive research to understand pollution characteristics and environmental impacts (Hilson, 2000; Lu, 2005). Additionally, a data comparative analysis is conducted to compare pollution data across stages and regions, revealing the long-term evolution patterns and cumulative effects of pyrite pollution.

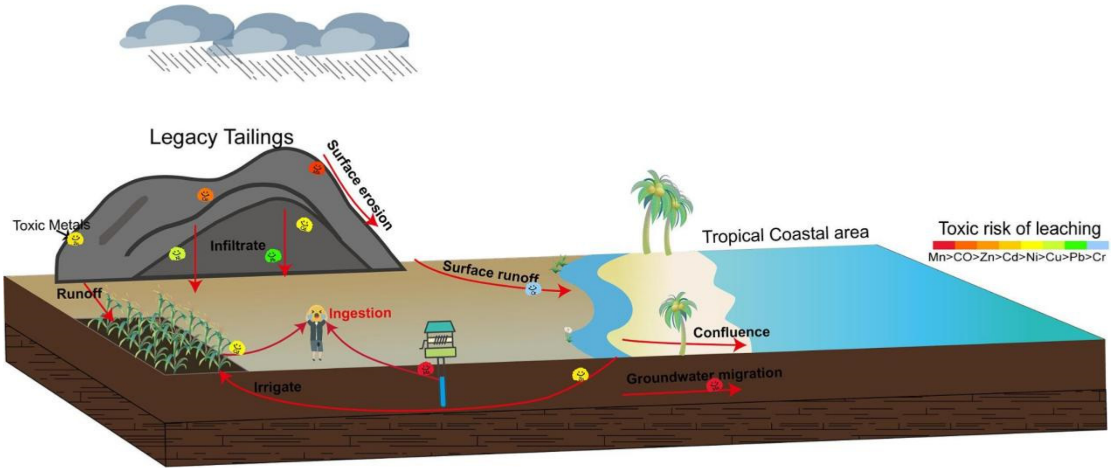

Figure 1. The environmental impact effect of heavy metal pollution (Ma et al., 2024)

2. Sources and Characteristics of Pyrite Pollution

2.1. Distribution and Current Status of Pyrite Exploitation

Globally, pyrite resources are abundant, primarily distributed in North Africa, the Middle East, North America, and other regions. China, as a major pyrite reserve, has significant deposits concentrated in the middle and lower reaches of the Yangtze River and southwestern areas (Liu et al., 2010; Wang et al., 2012). With economic development, the scale of pyrite mining has expanded continuously. However, exploitation methods vary across regions, with some areas relying on outdated technologies that result in severe resource wastage and environmental pollution (Hilson, 2003; Pagnanelli et al., 2004).

2.2. Primary Sources of Pyrite Pollution

During pyrite mining, large quantities of waste residues are generated, containing harmful substances such as sulfides and heavy metals. Under rainwater leaching, these residues easily form acid mine drainage (AMD), polluting nearby water bodies and soil (Singer & Stumm, 1970; Nordstrom & Alpers, 1999). In the beneficiation process, chemicals like collectors and frothers can escape into the environment, further harming ecosystems. Smelting processes emit exhaust gases rich in sulfur dioxide (SO_2), a major contributor to atmospheric pollution (Adams et al., 2007; Martín et al., 2014). Additionally, improperly treated smelting residues pose long-term environmental risks (Bonnail et al., 2016).

2.3. Characteristics of Pyrite Pollutants

Sulfides in pyrite pollutants are prone to oxidation in natural environments, generating sulfuric acid and causing environmental acidification (Luther, 1987; McKibben & Barnes, 1986). Heavy metals such as iron (Fe), copper (Cu), zinc (Zn), and cadmium (Cd) exhibit toxicity, persist in the environment, and tend to bioaccumulate, threatening ecosystems and human health (Fernández-Caliani et al., 2009; Hinojosa et al., 2008). The migration and transformation of these pollutants are highly complex, influenced by factors like soil pH, redox potential, and organic matter content (Gál et al., 2003; Aguilar et al., 2004). These factors drive chemical reactions and morphological changes across environmental media, altering pollutant toxicity and bioavailability.

3. Long-term Evolution of Pyrite Pollution

3.1. Initial Contamination Stage (Early Mining Phase – Several Years Later)

During the early stages of pyrite mining, pollution is concentrated near mining sites. Waste residue stockpiles occupy vast land areas, leaching harmful substances into soil and groundwater (Simon et al., 1999; Gabari et al., 2017). Untreated wastewater discharges contaminate surface water, elevating acidity, chemical oxygen demand (COD), and heavy metal concentrations, which impair aquatic life (Nieto et al., 2007; Cánovas et al., 2007). Dust emissions degrade local air quality, reducing visibility and affecting residents' livelihoods. At this stage, initial ecosystem damage manifests as reduced vegetation cover and biodiversity loss (Hilson, 2000).

3.2. Mid-term Diffusion Stage (Several Years – Decades Later)

Over time, weathering of waste residues and transport via groundwater and surface runoff spread contamination to surrounding areas (Fernández-Caliani et al., 2009; Romero et al., 2006). The formation and spread of AMD exacerbate water acidification, further increasing COD and heavy metal levels, devastating aquatic habitats (Sarmiento et al., 2009). In soils, heavy metal accumulation alters bioavailability, harming microbial communities and plant growth, leading to soil fertility decline and intensified ecosystem degradation (Hinojosa et al., 2008). Additionally, atmospheric SO_2 and other acid gases disperse, transform, and settle, contributing to regional acid rain and broader ecological impacts (Adams et al., 2007).

3.3. Long-term Accumulation and Stabilization Stage (Decades – Centuries Later)

Under prolonged natural and anthropogenic influences, pyrite pollution stabilizes into distinct spatial patterns (Gabari et al., 2017). Some pollutants persist in soils and sediments as insoluble or residual forms (Fernández-Caliani et al., 2009). However, environmental changes (e.g., acid rain, floods) may reactivate these pollutants, posing long-term risks (Nordstrom & Alpers, 1999). Ecosystem structure and function suffer severe, often irreversible damage: soil biodiversity plummets, soil food chains collapse, and critical services like nutrient cycling and organic decomposition diminish (Hinojosa et al., 2008). Aquatic ecosystems experience biodiversity collapse, ecological imbalance, and loss of ecosystem services (Bonmail et al., 2016).

4. Cumulative Effects of Pyrite Pollution on the Environment

4.1. Cumulative Effects on the Soil Environment

Long-term pyrite pollution leads to reduced soil biodiversity, with significant declines or even extinction of microorganisms, animals, and plant species critical to soil fertility and ecosystem functions (Fernández-Caliani et al., 2009; Gabari et al., 2017). The soil food chain is disrupted; for instance, large soil organisms such as earthworms exhibit decreased populations and activity in polluted environments, impairing organic matter decomposition and nutrient cycling (Hinojosa et al., 2008). Concurrently, soil microbial community structures shift: beneficial microorganisms decline, while pollution-tolerant species proliferate, further degrading soil ecosystem functionality (Aguilar et al., 2004). Ultimately, soil ecosystem services—such as nutrient cycling and organic decomposition—are weakened, reducing soil productivity and stability (Gál et al., 2003).

4.2. Cumulative Effects on the Aquatic Environment

Pyrite pollution causes long-term degradation of water quality in rivers, lakes, and other surface water bodies (Nieto et al., 2007; Cánovas et al., 2007). Acid mine drainage (AMD) increases water acidity and elevates chemical oxygen demand (COD), while heavy metals exceed safe thresholds in water systems (Singer & Stumm, 1970). Acidic conditions devastate aquatic habitats, rendering many species unable to survive and reducing biodiversity (Bonmail et al., 2016). Heavy metals undergo bioaccumulation in aquatic organisms and biomagnify through food chains, disproportionately harming higher trophic levels (e.g., fish, birds) and destabilizing aquatic ecosystems (Fernández-Caliani et al., 2009). Pollutants infiltrating groundwater systems migrate and accumulate over time due to slow groundwater flow rates, degrading water quality and threatening drinking water safety (Adams et al., 2007).

4.3. Cumulative Effects on the Atmospheric Environment

Sulfur dioxide (SO_2) and other acidic gases emitted during pyrite smelting disperse, transform, and settle in the atmosphere, causing long-term cumulative impacts on regional air quality (Martín et al., 2014). These gases react with water vapor to form acid rain, increasing the frequency and intensity of acid deposition, which indirectly pollutes soil, water, and vegetation (Nordstrom & Alpers, 1999). Additionally, acidic gases participate in photochemical reactions, exacerbating photochemical pollution (e.g., smog), reducing atmospheric visibility, and harming transportation and human health (Hilson, 2003). Dust generated during mining and processing operations suspends, transports, and settles in the atmosphere, elevating particulate matter (PM) concentrations and degrading air quality (Liu et al., 2010).

4.4. Cumulative Effects on the Entire Ecosystem

The cumulative impacts of pyrite pollution on soil, water, and air are interwoven, collectively degrading ecosystems (Fernández-Caliani et al., 2009; Romero et al., 2006). Pollutants in soil, water, and air undergo complex biogeochemical cycles, transforming and transferring across environmental media (Lu, 2005). This alters interactions and feedback mechanisms among ecosystem components. For example, heavy metals from contaminated water infiltrate terrestrial ecosystems via food chains, while atmospheric acid rain exacerbates soil and water pollution (Hinojosa et al., 2008). These cumulative effects severely compromise ecosystem structure and function: biodiversity plummets, ecological balance collapses, and critical ecosystem services—such as water retention, soil conservation, and habitat provision—are lost (Gabari et al., 2017).

5. Research Progress on Pollution Control and Prevention of Pyrite Mines

5.1. Pollution Control Technologies and Methods

5.1.1. Wastewater Treatment Technologies

The physical precipitation method utilizes gravity to separate solid particles from wastewater via sedimentation. While simple to operate, its effectiveness in removing dissolved pollutants is limited (Romero et al., 2006). Chemical redox methods involve adding oxidizing or reducing agents to convert harmful substances into non-toxic or easily separable forms. For instance, ferrous sulfate can effectively remove heavy metal ions from acidic wastewater, though chemical costs are relatively high (Civeira et al., 2016). Biological treatment methods leverage microbial metabolism to degrade pollutants, offering advantages such as low cost and no secondary pollution. However, they require longer treatment times and depend heavily on maintaining optimal microbial environments. In practical engineering applications, a combination of technologies is often employed to enhance efficiency. For example, physical precipitation is first used to remove large suspended particles, followed by chemical redox or biological treatment to address heavy metals and acidic components, ensuring compliance with discharge standards (Pagnanelli et al., 2006).

5.1.2. Waste Residue Treatment and Disposal

Stabilization/solidification technology involves adding cement, lime, or other solidifying agents to immobilize hazardous substances within waste residue, reducing their migration and leaching (Simón et al., 2001). While effective, the long-term stability of solidified residues requires further study. Bioremediation employs microorganisms or plants to degrade pollutants in waste residue, offering environmental friendliness and cost-effectiveness, though remediation times are prolonged for highly contaminated residues. Ecological restoration constructs artificial ecosystems (e.g., wetlands, vegetation cover) to rehabilitate and stabilize waste residues. Recent advancements in these technologies provide more options for pyrite waste management. Proper disposal reduces long-term environmental risks and enables resource recovery, such as extracting valuable metals from residues.

5.1.3. Atmospheric Pollution Prevention

Pyrite mining enterprises primarily employ flue gas desulfurization technologies, including wet and dry methods. Wet desulfurization uses water or absorbents to chemically react with sulfur dioxide (SO_2), forming sulfates. While highly efficient, it suffers from high absorbent consumption and equipment corrosion. Dry desulfurization relies on solid adsorbents to capture SO_2, offering lower investment costs and simpler operation, albeit with reduced efficiency. For dust removal, electrostatic precipitation and baghouse filtration are widely used. Electrostatic precipitation charges dust particles via a high-voltage electric field, achieving high efficiency for large gas volumes but requiring complex equipment and high energy consumption. Baghouse filtration separates dust via filter materials, providing high efficiency and stable operation, though filter bags require frequent replacement due to wear. Concurrently, clean energy integration (e.g., solar, wind) is increasing in pyrite operations, reducing reliance on traditional energy sources and lowering emissions. Progress has also been made in flue gas recycling technologies, where treated gases are repurposed as process gases or fuel, enhancing resource utilization efficiency.

5.2. Pollution Prevention Strategies and Policies

5.2.1. Environmental Regulation and Legal Standards

Domestic and international environmental regulations and standards have been established to govern pyrite mining, processing, and utilization. These frameworks play a critical role in regulating corporate practices, controlling pollutant emissions, and promoting cleaner production. For example, standards for wastewater discharge, flue gas emissions, and waste residue disposal during pyrite mining require enterprises to adopt effective pollution control measures to ensure compliance (Kroll, 2002). However, challenges persist in enforcement, including non-compliant emissions by some companies and insufficient regulatory oversight. To address these issues, stronger enforcement of regulations, improved monitoring mechanisms, and stricter penalties for violations are needed. Additionally, regulations and standards should be periodically updated to address emerging pollution challenges in pyrite mining, enhancing their scientific rigor and operational feasibility (Hilson, 2000).

5.2.2. Source Control and Cleaner Production

In the pyrite industry, source control and cleaner production are vital for pollution reduction. During mine planning, site selection should avoid ecologically sensitive areas and water source protection zones (Zhang et al., 2018). Advanced mining technologies and equipment should be promoted to improve mining recovery rates and reduce waste residue generation (Hilson, 2000). Optimized mineral processing can enhance efficiency, minimize the use of beneficiation reagents, and reduce environmental contamination from reagent leakage (Simon et al., 2005). Resource integration and utilization—such as recovering associated minerals from pyrite—boost resource efficiency and cut waste emissions. Supportive policies, including tax incentives and financial subsidies, alongside technical assistance systems, can encourage enterprises to develop and adopt cleaner production technologies, fostering sustainable development in the pyrite industry.

5.2.3. Ecological Restoration and Compensation Mechanisms

For ecosystems damaged by pyrite pollution, restoration strategies include vegetation recovery, soil remediation, and aquatic ecosystem rehabilitation (Figure 2). Vegetation recovery involves planting pollution-tolerant species and improving soil conditions to enhance ecosystem stability and functionality (Simón et al., 2005). Soil remediation techniques (e.g., soil washing, bioremediation) remove contaminants and restore soil quality. Aquatic ecosystem rehabilitation requires water purification, sediment remediation, and re-establishing biological communities to revive ecological functions. Ecological compensation mechanisms are critical for addressing pollution impacts. By establishing equitable compensation policies for affected regions and communities, ecological restoration efforts can be incentivized (Hilson, 2000. However, challenges remain in application, such as unstable funding sources and unscientific compensation criteria. To ensure long-term sustainability, compensation policies must be refined, with emphasis on stable funding and science-based standards (Adams et al., 2007).

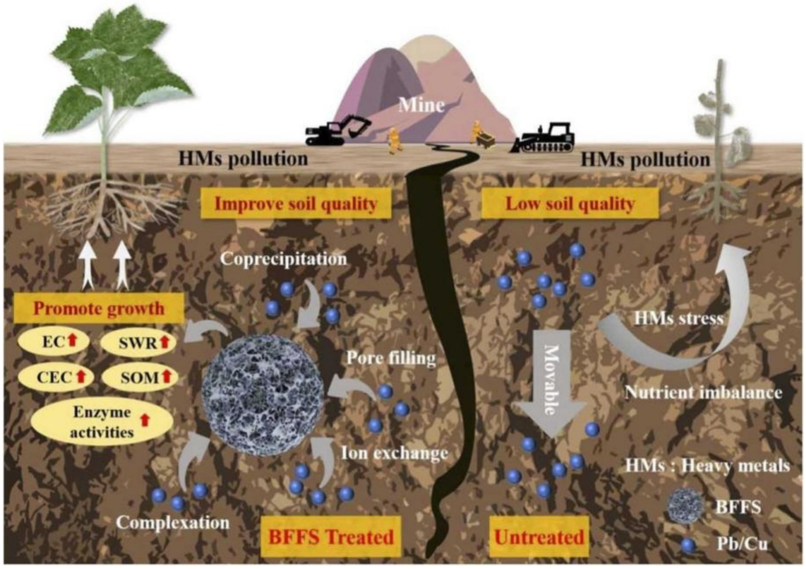

Figure 2. New materials are used to repair heavy metal pollution (Li et al., 2024)

6. Conclusion

The long-term evolution process of pyrite pollution can be divided into three distinct stages: initial contamination phase, intermediate diffusion phase, and long-term accumulation and stabilization phase, each characterized by unique pollution features and environmental impacts. During the initial stage, pollution primarily concentrates around mining areas, causing preliminary damage to local ecosystems. In the intermediate phase, the pollution scope gradually expands with complex chemical reactions and migration-transformation of pollutants in the environment, leading to intensified ecosystem degradation. The long-term accumulation and stabilization stage witnesses the formation of relatively stable pollution patterns in specific regions, yet retains potential threats, while ecosystem structure and functionality suffer severe, difficult-to-restore damage.

Pyrite pollution demonstrates significant cumulative effects on various environmental elements. Regarding soil environment, it induces soil acidification, structural deterioration, heavy metal accumulation, and ecosystem degradation. For aquatic systems, it causes surface water quality deterioration and groundwater contamination with cumulative effects. Atmospheric impacts include acid rain deposition, photochemical pollution, and elevated particulate matter concentrations. At the ecosystem level, it poses long-term irreversible risks including biodiversity collapse, ecological imbalance, and loss of ecosystem service value.

In pollution control and prevention, current technologies including wastewater treatment, waste residue disposal, and air pollution prevention have achieved certain successes, yet exhibit limitations in practical applications. Although existing pollution prevention strategies and policy implementations have played crucial roles in controlling pyrite pollution, further refinement and enhanced enforcement remain necessary. Overall, the pyrite pollution issue demonstrates complexity and persistence, requiring continuous attention and effective measures for systematic governance and long-term prevention.

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