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ENVIRONMENTAL ISSUES IN MINING: A COMPREHENSIVE REVIEW OF CHALLENGES AND STRATEGIES FOR MITIGATION AND REHABILITATION

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Abstract: *Mining significantly contributes to global economic development, accounting for approximately 6% of global GDP. However, its environmental impacts are severe, including acid mine drainage (AMD), water and air pollution, soil degradation, biodiversity loss, and greenhouse gas emissions. This study critically examines these challenges and evaluates mitigation and rehabilitation strategies for sustainable mining.*

A comprehensive review of peer-reviewed literature and case studies (1990–2023) was conducted, focusing on environmental impacts, mitigation measures, and rehabilitation outcomes. Key findings reveal that AMD contaminates water with heavy metals, while mining contributes significantly to greenhouse gas emissions and particulate matter, exacerbating climate change and public health risks. Biodiversity loss, particularly in sensitive regions like the Amazon, highlights mining's ecological footprint. Mitigation strategies, such as renewable energy adoption, advanced water treatment systems, and circular economy principles, show promise but face challenges in scalability and cost. Rehabilitation efforts, including reforestation, land reshaping, and biodiversity offsets, have successfully restored degraded landscapes but require robust regulation and community participation. This study emphasizes the importance of integrating technological innovation, stringent regulations, and stakeholder engagement to address mining's environmental legacy. Future research should focus on cost-effective technologies, socioeconomic impacts, and combating illegal mining to balance economic development with environmental sustainability.

Keywords: *Acid Mine Drainage (AMD), Biodiversity Loss, Sustainable Mining Practices, Rehabilitation Strategies, Land Restoration, Greenhouse Gas Emissions, Water and Air Pollution*

1. Introduction

1.1. Background

Mining, the process of extracting valuable minerals and resources from the Earth, has played an instrumental role in shaping human civilization, fuelling industrialization, and underpinning technological advancements. It remains a cornerstone of the global economy, supplying essential materials such as metals, rare earth elements, and fossil fuels for infrastructure development and the manufacture of advanced technologies. The mining sector contributed approximately 6% to the global GDP, underscoring its vital role in contemporary economic systems. [1]. However, the environmental consequences of mining have sparked significant concerns, particularly regarding its sustainability. Mining operations profoundly alter landscapes, disrupt ecosystems, and generate substantial waste, resulting in a wide array of environmental challenges. One of the most pressing issues is acid mine drainage (AMD), a chemical phenomenon that occurs when sulfide minerals exposed during mining oxidize, producing sulfuric acid. This acid mobilizes heavy metals, contaminating nearby water bodies and soils. The environmental ramifications of AMD are severe, often persisting for decades or even centuries after the cessation of mining activities, [2].

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Another major environmental consequence of mining is air pollution. The processes involved in the extraction, transportation, and processing of minerals release significant amounts of particulate matter, toxic fumes, and greenhouse gases (GHGs). Globally, mining accounts for approximately 7% of GHG emissions, with coal mining alone contributing a significant share of methane emissions, a GHG with a global warming potential 25 times that of carbo dioxide [3] Smelting operations exacerbate these impacts, releasing sulfur dioxide and heavy metals, which contribute to acid rain and pose health risks, including respiratory illnesses, to surrounding populations. The environmental degradation associated with mining also extends to biodiversity loss, particularly in ecologically sensitive regions such as tropical forests, which are home to a substantial portion of the planet's biodiversity. Mining in these areas has led to deforestation, habitat fragmentation, and species extinctions, threatening critical ecosystem services such as water purification, carbon sequestration, and soil fertility [4]. The loss of biodiversity further exacerbates ecological imbalances and undermines long-term environmental stability.

The socioeconomic dimensions of mining add further complexity to its environmental implications. While mining activities contribute to employment generation and infrastructure development, they often lead to the displacement of local communities, exacerbate land-use conflicts, and expose vulnerable populations to environmental hazards. Resource-rich regions frequently experience the "resource curse," characterized by a paradoxical coexistence of economic wealth from resource extraction with environmental degradation and social inequities [5]. In response to these challenges, the concept of sustainable mining has emerged as a framework to reconcile the economic, environmental, and social dimensions of mining. Sustainable mining practices emphasize the adoption of environmentally friendly extraction technologies, the implementation of circular economy principles, and the rehabilitation of degraded landscapes. Notable strategies include integrating renewable energy sources into mining operations, employing advanced water treatment technologies to mitigate AMD, and restoring mined lands through reforestation and the reintroduction of native vegetation. The continued reliance on mining to sustain global economic development necessitates a critical examination of its environmental impacts. These impacts—ranging from soil erosion and water and air pollution to habitat destruction and biodiversity loss—are particularly acute in regions where environmental regulations are weak or poorly enforced, often in developing countries [6]. As the global demand for minerals grows, there is an urgent need to adopt sustainable mining practices that balance economic development with environmental stewardship. This paper aims to provide an in-depth analysis of the environmental challenges associated with mining and evaluate strategies for mitigating these impacts. By integrating sustainable practices, the mining industry can transition towards a model that minimizes ecological harm while contributing to economic growth and social well-being.

1.2. Research Problem and Rationale

While significant research has addressed the environmental impacts of mining, there remains a gap in the understanding of effective, context-specific mitigation and rehabilitation strategies. Moreover, numerous strategies exist, but their success varies depending on regional context, type of mining, and enforcement mechanisms. This paper addresses the research gap by critically reviewing the environmental issues associated with mining, focusing on both the challenges and solutions for mitigating and rehabilitating these effects.

1.3. Objectives and Scope

The objective of this study is to provide a comprehensive review of environmental issues related to mining and to analyze the mitigation and rehabilitation strategies employed to address these challenges. This paper will:

- Review key environmental challenges, such as soil erosion, water pollution, and deforestation.
- Discuss various mitigation strategies, including pollution control, waste management, and reforestation efforts.
- Analyze rehabilitation strategies, focusing on land restoration, post-mining land use, and the recovery of ecosystems.
- Evaluate the effectiveness of these strategies through case studies and literature.

2. Literature Review

2.1. Environmental Impacts of Mining

Mining is essential for obtaining raw materials necessary for industrial and technological advancements. However, mining activities can cause extensive environmental degradation, leading to significant impacts on air, water, soil, and biodiversity. This section reviews the major environmental concerns related to mining,

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drawing on the latest literature and research findings to understand the scope of these issues and propose mitigation strategies.

Water Pollution: Acid Mine Drainage and Heavy Metals

Water pollution is among the most critical environmental issues associated with mining, primarily resulting from acid mine drainage (AMD) and the release of heavy metals. AMD occurs when sulfide minerals exposed during mining activities react with oxygen and water, producing sulfuric acid. This acidic runoff mobilizes toxic heavy metals, such as arsenic, cadmium, and lead, which contaminate water bodies, leading to the degradation of water quality. The presence of these pollutants in water sources renders the water unsuitable for both aquatic life and human consumption. The persistence of heavy metals in the environment further exacerbates the problem, as they bioaccumulate in aquatic organisms and terrestrial food chains, posing long-term health risks, including neurological damage and organ dysfunction. In addition to impacting human health, contaminated water also affects agricultural productivity, particularly by rendering irrigation water unsafe and diminishing water availability in affected regions. Furthermore, mining tailings, waste, and other byproducts contribute to the spread of contamination, particularly when containment systems fail, leading to widespread environmental degradation.

Addressing water pollution from mining requires the implementation of effective treatment technologies, such as neutralization methods to reduce acidity and filtration systems to remove heavy metals. Additionally, comprehensive mine site rehabilitation, proper waste management practices, and stringent regulatory frameworks are necessary to prevent and mitigate contamination, ensuring the long-term sustainability of water resources in mining areas. [7], Studied of copper and gold mining sites in the U.S., finding that AMD remediation remains costly and often insufficient, even with advanced treatment systems. The study highlights the potential of bioremediation and constructed wetlands, but scaling these technologies for large operations remains a challenge due to high costs and environmental variability. Similarly, [8] explored passive treatment systems (PTS) for AMD management, noting their effectiveness in low-flow conditions and their potential as a cost-effective alternative in remote locations, though site-specific factors must be considered.

Mining operations also release heavy metals into water systems, accumulating in aquatic ecosystems and impacting both biodiversity and human health. (9), Highlighted elevated levels of heavy metals in Southeast Asia’s river systems, contaminating local water sources. The study advocates for integrated pollution control measures such as sediment traps and flocculation agents to prevent contamination. Additionally, mining processes, particularly in gold and coal extraction, use harmful chemicals like mercury and cyanide, which can severely pollute local water supplies. The cyanide spills in Ghana and South Africa have caused extensive contamination of rivers and groundwater, harming aquatic ecosystems and local communities [10]. These incidents emphasize the need for effective pollution control measures and the careful management of hazardous chemicals in mining.

Soil and Land Degradation

Mining, particularly open-pit mining, exerts a substantial negative impact on land quality, resulting in soil erosion, loss of fertility, and overall land degradation. The process of removing vegetation, soil, and rock to access mineral deposits leaves the underlying soil vulnerable to erosion by wind and water. This disruption of the natural landscape significantly alters soil structure, diminishing its ability to retain moisture and essential nutrients. The loss of soil structure and fertility is particularly problematic for agricultural productivity, as topsoil, which is rich in organic material and vital for plant growth, is often displaced or destroyed during mining activities. As a result, the land becomes less productive and more susceptible to further degradation. The exposure of underlying layers of soil and rock also creates long-lasting environmental challenges, such as the accumulation of toxic metals and chemicals, which can leach into the soil and contaminate surrounding areas. In addition to the direct impacts on agriculture, land degradation caused by mining can lead to the loss of biodiversity and the disruption of local ecosystems. The removal of natural habitats and the alteration of landforms often result in reduced habitat availability for wildlife, contributing to declines in species populations. Efforts to mitigate soil and land degradation from mining include implementing erosion control measures such as vegetation restoration, terracing, and the stabilization of mining sites through soil amendments. The use of sustainable mining practices, including proper waste management and the rehabilitation of mined areas, is essential to prevent further land degradation and promote ecological recovery. By prioritizing land restoration and implementing best practices in land management, the long-term environmental impacts of mining can be minimized. [11], the effects of open-pit mining on soil fertility

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in South American mining regions were explored. The findings revealed that mining operations led to a 40% decrease in organic matter content in impacted soils. While land reclamation practices such as revegetation and organic soil amendments show promise in restoring soil health, financial constraints and regulatory shortcomings often hinder their effective implementation. The removal of vegetation for mining also exposes soil to increased erosion, making it vulnerable to degradation. This renders the land unsuitable for future agricultural use [12]. Additionally, the accumulation of mining waste materials, particularly tailings, further exacerbates land degradation. Tailings dams are prone to failure, which can release toxic chemicals into the environment, worsening soil and land quality. [13] The examination of the impact of tailings dam failures in Brazil and the Philippines, revealing catastrophic consequences for land quality, agriculture, and human populations. The study advocates for innovations in tailings management, such as dry-stacking and geopolymer technology, to mitigate environmental risks associated with these waste materials.

Air Pollution: Greenhouse Gas Emissions, Sulfur Dioxide, and Particulate Matter

Mining operations significantly contribute to air pollution through the release of greenhouse gases (GHGs), sulfur dioxide (SO_2), and particulate matter (PM), posing environmental and health risks. Key processes, including excavation, transportation, and mineral processing, release carbon dioxide (CO_2) and methane (CH_4), with methane—a byproduct of coal mining—being a particularly potent GHG with a global warming potential 25 times that of CO_2, [3]. Mining activities collectively account for approximately 7% of global GHG emissions. Sulfur dioxide emissions primarily occur during the smelting of sulfur-containing ores, leading to acid rain and environmental degradation. SO_2 also poses health risks such as respiratory issues and aggravated conditions like asthma. Similarly, particulate matter generated by excavation, blasting, and transport includes fine particles (PM2.5) capable of penetrating the respiratory system and causing severe health problems, including cardiovascular diseases.

The environmental impacts of these pollutants extend to climate change, soil and water acidification, and reduced air quality, directly affecting surrounding ecosystems and communities. Mitigation strategies include adopting renewable energy, methane capture technologies, sulfur capture systems like flue gas desulfurization, and dust suppression measures. These efforts, combined with stringent regulatory frameworks, are essential for reducing air pollution and fostering more sustainable mining practices. The carbon footprint of the mining sector in Australia, revealed that the sector contributes to approximately 7% of global GHG emissions. Energy-intensive processes like ore extraction and smelting are major contributors to this high level of emissions. The authors recommend transitioning to renewable energy sources such as solar and wind power to reduce reliance on fossil fuels and minimize mining's environmental impact, [14].

The studied sulfur emissions from mining operations, highlighting that SO_2 contributes to acid rain, which harms ecosystems and human health. [15]. The study found that air pollution control technologies, like flue gas desulfurization, could significantly reduce SO_2 emissions, though these technologies may be too costly for implementation in low- income regions. Furthermore, particulate matter generated during mining operations has severe health effects, particularly respiratory diseases. Mining operations in China release substantial amounts of particulate matter, contributing to chronic respiratory conditions in nearby populations. Dust suppression technologies, such as water spraying and dust-absorbing polymers, could help mitigate the effects of airborne particulate matter, though their implementation is inconsistent across regions, [16]. In regions such as the Middle East and parts of Africa, dust from mining operations has been linked to respiratory illnesses among local populations, emphasizing the need for effective air quality management. For instance, in Ghana, a study involving 1,001 male miners from the Obuasi and Tarkwa mines revealed a high prevalence of respiratory disorders, including asthma (47.55%), pneumonia (14.29%), bronchitis (9.69%), and emphysema (5.10%). Coughing was the most commonly reported symptom (35.4%), with socio-demographic factors and environmental exposures playing a significant role in the development of these conditions [17]. This highlights the need for improved working environments and health education to reduce respiratory diseases among miners.

In South Africa, the mining industry has long been associated with occupational respiratory diseases, particularly silicosis, caused by exposure to crystalline silica dust. Pulmonary silicosis remains a significant health issue, first described in South African gold miners in the early 1900s, and continues to affect workers in the mining sector. The long-term health impacts of silica exposure underscore the necessity for stringent air quality standards in mining areas. Furthermore, a systematic review on desert dust in arid regions, including parts of Africa and the Middle East, noted that dust storms contribute to mortality and morbidity, particularly respiratory and circulatory diseases. This review highlighted the need for better understanding of the health effects of desert dust to inform protective policies [18].

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Biodiversity Loss: Habitat Destruction and Ecosystem Disruption

Mining activities significantly contribute to biodiversity loss through the destruction of habitats, ecosystem fragmentation, and environmental pollution. Large-scale mining operations often involve deforestation and clearing vast tracts of land, leading to the displacement of wildlife and the eradication of plant species. This habitat destruction disrupts ecological balance, reducing species diversity and threatening the survival of endemic and endangered species. Ecosystem fragmentation caused by mining infrastructure, such as roads and pits, isolates wildlife populations, limiting their access to resources and mating opportunities, which can result in genetic bottlenecks. Moreover, mining-related pollution, including the release of heavy metals, sedimentation, and acid mine drainage, contaminates soil and water bodies, severely affecting aquatic ecosystems and poisoning flora and fauna. The cumulative effects of these disruptions undermine ecosystem services, such as water purification, carbon sequestration, and soil fertility, exacerbating environmental degradation and making ecosystem recovery a prolonged and challenging process. [19] estimate that deforestation and land-use changes, including mining, contribute 12–20% of global anthropogenic GHG emissions annually. Additionally, soil degradation caused by mining further diminishes carbon storage potential, compounding the environmental impact. Although reforestation and ecosystem restoration can mitigate these effects, the recovery of carbon sequestration functions is a lengthy process, often taking decades. The study underscores the urgent need for sustainable mining practices and robust forest conservation measures to mitigate climate change effectively.

Gold mining in the Amazon has led to widespread deforestation, significantly harming the region's ecosystems and the livelihoods of indigenous communities [20]. Mining operations clear large areas of forests, wetlands, and grasslands, disrupting critical habitats and threatening biodiversity. This environmental degradation not only displaces wildlife but also negatively affects local water quality through contamination from toxic chemicals, such as mercury, used in mining processes. For indigenous communities, the destruction of their land means the loss of resources essential for their survival and cultural practices, leading to displacement and increased vulnerability. The cumulative impacts of mining underscore the urgent need for more sustainable practices to protect the Amazon's ecological integrity and support the well-being of its indigenous peoples.

The impact of mining on biodiversity in the Amazon rainforest, finding that mining led to the destruction of habitats for endangered species, including jaguars and macaws. The researchers argue for the implementation of biodiversity offset programs that aim to restore habitats lost during mining activities [21]. However, these programs are often hindered by inadequate funding and monitoring, necessitating a more robust approach that integrates ecosystem-based management. Environmental impact assessments (EIAs) play a crucial role in mitigating biodiversity loss in mining projects. A reviewed of the effectiveness of EIAs, finding revealed that while they are legally required in many countries, they often fail to account for the long-term ecological consequences of mining [22]. To improve the effectiveness of EIAs, the authors recommend enhancing their transparency and rigor, incorporating comprehensive biodiversity studies, and involving local communities in decision-making processes.

Table 1. Summary of Mining-Related Environmental Impacts

Environmental Aspect	Description	Impact	Consequences
Deforestation and Habitat Loss	Clearing of large land areas for mining operations, destroying vegetation and wildlife habitats.	Loss of biodiversity, disruption of ecosystems, and reduction in carbon sequestration capacity.	Accelerated climate change, endangerment of species, and displacement of indigenous communities.
Water Pollution	Contamination of water bodies from mining chemicals such as mercury, cyanide, and acid mine drainage.	Degradation of water quality, harm to aquatic ecosystems, and health risks for nearby communities.	Limited access to safe drinking water, reduced agricultural productivity, and long-term ecosystem damage.
Soil Erosion and Degradation	Removal of vegetation and exposure of soil during mining activities.	Increased soil erosion, loss of fertility, and accumulation of mining waste (tailings).	Reduced land suitability for agriculture and risk of tailings dam failures causing widespread contamination.
Air Pollution	Emission of dust, particulate matter, and gases such as sulfur dioxide and methane during mining operations.	Poor air quality, respiratory illnesses, and contribution to greenhouse gas emissions.	Health issues in local populations, acid rain formation, and exacerbation of global warming.
Biodiversity Loss	Disruption and destruction of habitats due to mining and pollution.	Decline in species populations and ecosystem fragmentation.	Imbalanced ecosystems, extinction of endangered species, and loss of ecosystem services.

2.2. Mitigation and Rehabilitation Strategies for Mining Activities

Mining operations have a significant environmental impact, affecting water, soil, air, and biodiversity. To address these issues, effective mitigation and rehabilitation strategies are essential. These strategies aim to minimize environmental damage during mining activities (mitigation) and restore ecosystems after mining ceases (rehabilitation). Numerous active and passive techniques have been developed, with academic research providing valuable insights into their effectiveness and limitations. This section presents a comprehensive overview of mitigation and rehabilitation strategies, drawing on key literature and studies.

Mitigation Strategies

Mitigation strategies focus on reducing or preventing environmental damage during mining operations through pollution control, habitat restoration, and responsible waste management. Key mitigation measures include:

Pollution Control Technologies

Mining activities generate significant air pollution, primarily in the form of dust and hazardous gases like sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Pollution control technologies are therefore critical for reducing emissions and improving air quality.

- Dust Suppression: Dust control is a primary concern in mining operations, particularly in open-pit mining. Several dust suppression methods, including water spraying, windbreaks, and the application of polymer-based dust suppressants, have been shown to effectively reduce particulate matter emissions. A highlight of the role of water sprays and windbreaks in reducing airborne dust in mining operations [23]. The use of polymer-based dust suppressants, demonstrating that they can reduce particulate matter by up to 80%, though regular maintenance is required to maintain their effectiveness [24].
- Gas Emission Reduction: Mining operations also release gases like sulfur dioxide and nitrogen oxides, contributing to air pollution and acid rain. To mitigate these emissions, technologies such as scrubbers and catalytic converters are used. Scrubbers and filters are effective in reducing the release of these hazardous gases, though their application is often limited to regions with stricter environmental regulations [25].

Reforestation and Afforestation

Reforestation is a vital mitigation strategy aimed at restoring ecosystems damaged by deforestation due to mining activities. Reforestation with native species is one of the most common and effective strategies for mitigating environmental degradation caused by mining. Successful reforestation efforts in Brazil and Indonesia have shown promising results, with biodiversity recovery and soil restoration being the key benefits of these initiatives [19]. Supports these findings, emphasizing the importance of using native species to ensure the long-term success of these efforts [20]

Waste Management

Improper disposal of mining waste, including tailings and waste rock, can lead to soil and water contamination. The management of mining waste is crucial in mitigating environmental harm. One of the main methods for managing mining waste is the use of tailings dams, which store waste materials generated during mining operations. However, these dams are prone to catastrophic failure, as demonstrated by the 2015 Samarco dam collapse in Brazil [26]. This disaster highlighted the importance of improving waste management practices and ensuring the safety of tailings storage facilities.

Habitat Protection and Restoration

Minimizing land disturbance by conserving or relocating natural habitats, and using reclamation methods to restore ecosystems, such as planting native vegetation and ensuring proper soil stability. These efforts help to preserve biodiversity and maintain ecological balance [27].

Sustainable Mining Practices

Implementing environmentally responsible mining practices, such as reduced extraction methods, energy-efficient processes, and the use of renewable energy, to reduce the environmental footprint of mining activities. This includes using technologies that minimize the need for water and energy [28].

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Table 2. Summary of Mitigation Strategies

Strategy	Description	Effectiveness
Pollution Control (Dust Suppression)	Techniques such as water spraying, windbreaks, and polymer-based dust suppressants to reduce airborne dust.	Highly effective, with water spraying and windbreaks reducing dust by up to 70%. Polymer suppressants can achieve up to 80% reduction but require maintenance.
Pollution Control (Gas Emission Reduction)	Use of scrubbers and catalytic converters to reduce sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions.	Effective in reducing gas emissions, particularly in regulated regions. However, costly and energy- intensive.
Waste Management	Use of tailings dams to store mining waste, and techniques like encapsulation and dry stacking to manage waste safely.	Often effective in the short term, but risks remain due to potential dam failures, as seen in high-profile mining disasters.
Cleaner Energy Sources	Integration of renewable energy sources like solar and wind to power mining operations and reduce reliance on fossil fuels.	Effective in reducing greenhouse gas emissions and improving sustainability, though initial costs may be high.
Biodiversity Offsets	Compensatory actions taken to preserve or restore biodiversity in areas impacted by mining, often through habitat restoration elsewhere.	Effectiveness depends on careful planning and monitoring; can be effective, but often has limited success due to implementation challenges.

2.3. Rehabilitation Strategies

Rehabilitation strategies focus on restoring mining-affected areas to a state that supports ecological functions and enables post- mining land use. These strategies aim to rehabilitate soil, restore biodiversity, and create viable land uses for the future.

- *Ecological Restoration:* Ecological restoration involves reintroducing native species, restoring ecological functions, and recovering biodiversity on mined lands. This strategy often includes planting native vegetation and rehabilitating wetlands to support ecosystem recovery. The successful ecological restoration of coal mining sites in the UK, where native vegetation was replanted, and wetlands were restored. The study emphasizes the importance of restoring ecosystem functions, including nutrient cycling and water filtration, to ensure that the land is capable of supporting diverse species once again [29].
- *Landform Reshaping:* Landform reshaping is an important strategy used to improve the physical characteristics of the land, reduce erosion risks, and support the establishment of vegetation. Describing how reshaping landforms in Australia’s mining regions has been used to create habitats for local wildlife and improve land stability for plant growth [30]. This strategy has been effective in reducing the risk of erosion and promoting vegetation recovery, ultimately aiding in the restoration of ecological functions in post-mining landscapes.
- *Post-Mining Land Use:* After the rehabilitation of mining sites, the land can be repurposed for various uses, including agriculture, forestry, or wildlife conservation. A studied documented the transformation of former mining sites in Canada into productive agricultural land or areas for wildlife conservation [29]. These case studies demonstrate how post-mining land use can contribute to the sustainable development of formerly degraded landscapes.

Water Treatment: Active and Passive Approaches

Water pollution, particularly from acid mine drainage (AMD) and heavy metal contamination, is one of the most critical environmental impacts of mining activities. Various methods have been developed to address water pollution, categorized into active and passive treatment approaches.

- *Active Water Treatment:* Active water treatment involves engineered solutions to address water pollution caused by AMD and heavy metals. One common method is the chemical neutralization of AMD, where alkaline chemicals, such as lime or sodium hydroxide, are added to contaminated water to neutralize acidity and precipitate heavy metals. The effectiveness of active treatment systems at U.S. mining sites, finding that while chemical neutralization was effective at reducing acidity, the treatment systems were costly, energy-intensive, and required ongoing maintenance [18]. This makes active treatment less sustainable in the long term.
- *Passive Water Treatment:* Passive water treatment relies on natural processes to treat contaminated water. One commonly used passive treatment method is the use of constructed wetlands, which rely on plants, soils, and microorganisms to filter out pollutants. The effectiveness of constructed wetlands in treating low to moderately polluted water, particularly in remote mining sites where active treatment is not feasible. The success of passive systems depends on various factors, such as water flow rate, pH levels, and temperature [31]. Another passive method is bioremediation, which uses microorganisms to degrade

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pollutants. The use of sulfate-reducing bacteria in mining sites in India and found promising results in reducing sulfate concentrations and heavy metals like arsenic and cadmium [32]. While bioremediation is cost-effective and environmentally friendly, its effectiveness is often site-specific, influenced by factors such as nutrient availability and temperature.

Soil Rehabilitation

Mining activities often lead to significant soil degradation, including erosion, fertility loss, and reduced plant growth capacity. Restoring soil health and preventing further degradation is crucial for ecological recovery.

- *Soil Amendments:* Soil amendments, such as organic matter, lime, and biochar, are commonly used to restore soil health. A review of soil amendment strategies in Central Asia, noting that adding organic materials like compost can improve soil fertility by increasing microbial activity and enhancing nutrient cycling [33]. Biochar, a form of charcoal produced from organic waste, has gained attention for its ability to improve soil structure, retain moisture, and increase fertility in highly degraded soils.
- *Reforestation and Vegetation Restoration:* Reforestation and vegetation restoration are key strategies for stabilizing soil, preventing erosion, and promoting ecological recovery. A studies on the deforestation efforts at coal mining sites in Australia revealed that introducing native plant species helped stabilize soil, reduce erosion, and restore biodiversity [34]. The study highlights the importance of using native plants to ensure the success of reforestation and the recovery of soil health.
- *Erosion Control:* Erosion control is vital for preventing further soil degradation, especially in open-pit mining areas. Common techniques for controlling erosion include the use of silt fences, erosion control blankets, and hydroseeding, a method where a mixture of seed, water, and mulch is sprayed over the soil. A studied conducted on erosion control in mining sites in Africa revealed that combining vegetation with physical barriers was the most effective approach for reducing soil erosion [35].

Air Quality Control

Mining operations are a major source of air pollution, particularly in the form of dust and particulate matter, as well as emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Effective air quality control strategies are essential for minimizing these environmental impacts.

- *Dust Suppression*: Dust suppression techniques, such as water spraying and polymer-based dust suppressants, have been shown to be effective in reducing airborne particulate matter. A studied found that polymer-based dust suppressants could reduce particulate emissions by up to 80% [36]. However, the study notes that these methods require regular application and maintenance to ensure long-term effectiveness.
- *Cleaner Energy Sources:* Transitioning to cleaner energy sources is a key strategy for reducing greenhouse gas emissions and improving air quality in mining operations. A study conducted on renewable energy integration in South African mines and found that solar power offers a viable solution for reducing emissions from energy- intensive mining operations [37]. The use of electric mining vehicles and battery storage systems can further reduce the sector's carbon footprint.
- *Emissions Control Technologies:* The installation of emissions control technologies, such as scrubbers and catalytic converters, is essential for reducing harmful air pollutants. A study [38] found that sulfur dioxide scrubbers significantly reduce air pollution from mining operations in the U.S., although the adoption of such technologies remains limited in regions with less stringent environmental regulations.
- *Habitat Restoration:* Revegetation and habitat restoration are essential for maintaining biodiversity after mining activities. Liu et al. (2021) A successful habitat restoration requires selecting appropriate plant species, ensuring soil health, and providing adequate moisture [39]. The study emphasizes the need for long-term monitoring to ensure that restored habitats support diverse species and ecological functions.
- *Biodiversity Offsets:* Biodiversity offsets are compensatory measures designed to balance the environmental damage caused by mining by preserving or restoring biodiversity in other areas. Meyer et al. (2020) found that while biodiversity offsets have the potential to mitigate habitat loss, their effectiveness is often compromised by poor planning, insufficient monitoring, and lack of enforcement. The study recommends a more stringent approach to offset implementation to ensure no net loss of biodiversity.

Species Translocation

In cases where habitat destruction is unavoidable, species translocation—relocating threatened species to new habitats— can help conserve biodiversity. A studied translocation effort in mining regions and found that while translocation can be successful in the short term, challenges such as genetic bottlenecks and establishing viable populations often hinder long-term success [40]. Their study emphasizes the importance of considering genetic diversity and the suitability of recipient habitats before undertaking translocation projects.

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Table 3. Summary of Rehabilitation Strategies

Strategy	Description	Effectiveness
Ecological Restoration	Reintroducing native species, restoring wetlands, and rebuilding ecological functions in mined areas.	Highly effective when native species are used, but requires long-term monitoring to ensure success in biodiversity recovery.
Landform Reshaping	Reshaping the land to reduce erosion, create stable landforms, and improve the suitability for plant growth and wildlife habitat.	Effective for reducing erosion and supporting vegetation recovery, but requires careful planning and ongoing maintenance.
Post-Mining Land Use	Transforming mined land for agricultural, forestry, or wildlife conservation purposes after rehabilitation.	Effective if managed properly; repurposing can create sustainable post-mining landscapes with diverse land uses.
Active Water Treatment	Use of chemical treatments (lime or sodium hydroxide) to neutralize acid mine drainage (AMD) and remove heavy metals.	Effective for immediate results, but expensive, energy-intensive, and requires long-term operation and maintenance.
Passive Water Treatment	Utilizing natural processes, such as constructed wetlands or bioremediation, to treat contaminated water.	Cost-effective and sustainable for low to moderately polluted sites but less effective in highly contaminated areas.
Soil Amendments	Adding organic matter, lime, or biochar to improve soil fertility, structure, and microbial activity in degraded mining areas.	Highly effective for improving soil health and fertility, especially when using organic amendments.
Revegetation and Vegetation Restoration	Planting native species and stabilizing soil to restore vegetation on mined land and prevent erosion.	Highly effective for restoring biodiversity and soil stability, especially when native species are carefully selected.
Erosion Control	Use of silt fences, erosion control blankets, and hydroseeding to reduce soil erosion and stabilize land in mining regions.	Effective in controlling erosion and promoting vegetation recovery, especially when combined with other rehabilitation strategies.
Species Translocation	Relocating threatened or endangered species to new habitats to preserve biodiversity after mining destroys their natural habitat.	Effective for short-term conservation but faces challenges with genetic diversity, ecological compatibility, and long-term survival.

2.4. Theoretical Frameworks for Environmental Sustainability in Mining

The theoretical frameworks underpinning environmental sustainability in mining draw on various interdisciplinary approaches. These frameworks help to understand how mining operations can be conducted with reduced environmental impact while balancing economic growth and community well-being. The following are some key theoretical frameworks influencing sustainable mining practices:

- *The Triple Bottom Line (TBL) Framework:* The Triple Bottom Line (TBL) framework, developed by Elkington, emphasizes three key pillars of sustainability: environmental, social, and economic. In the mining sector, TBL is applied to evaluate mining operations from a broader perspective that includes the environmental impacts of resource extraction, the social consequences for local communities, and the economic benefits of mining activities [41]. Many studies have utilized TBL to assess the broader sustainability of mining projects, suggesting that a holistic approach is essential for ensuring that mining delivers both economic and environmental benefits without neglecting social responsibility [42].
- *Ecological Modernization Theory (EMT):* Ecological Modernization Theory (EMT) posits that technological innovation and regulatory reforms can reconcile environmental protection with industrial development. EMT suggests that environmental concerns should not be viewed as a hindrance to economic growth but as opportunities for innovation and improved efficiency. Majo Research has explored how new technologies, like cleaner mining techniques and energy-efficient mining equipment, can mitigate environmental damage. The application of EMT in the mining sector calls for integrating innovative technologies that reduce emissions, improve waste management, and conserve water and energy resources [43].
- *The Precautionary Principle:* The Precautionary Principle plays a crucial role in addressing uncertain or unknown risks, which are often inherent in mining due to the complex and variable nature of environmental impacts. According to this principle, if an activity poses a risk of causing significant harm to the environment or human health, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically. This principle has been incorporated into various regulatory frameworks governing mining, particularly in relation to issues like acid mine drainage (AMD) and long-term contamination of ecosystems. Studies suggest that adopting precautionary measures in mining operations can significantly reduce environmental risks associated with unpredictable events like chemical spills or resource depletion [44]

- *Circular Economy Framework:* The Circular Economy (CE) framework promotes a shift from the traditional linear model of production and consumption (which is based on extracting, using, and disposing of resources) to a more sustainable system where resources are reused, recycled, and regenerated. In the mining industry, the CE framework advocates for practices like resource recycling, waste reduction, and the reuse of mining by- products. Research examined the application of circular economy principles in the mining sector, finding that integrating these practices can significantly reduce environmental degradation while enhancing economic performance [45]. For instance, using mining tailings to create new materials or reprocessing waste can reduce environmental impact and extend the lifespan of mining operations.

2.5. Theoretical Framework for Mitigation and Rehabilitation Strategies

The effectiveness of mitigation and rehabilitation strategies in mining can be understood through the lens of several critical theoretical frameworks. These frameworks emphasize the importance of integrating environmental considerations into mining operations and ensuring long-term sustainability:

- *Environmental Management Theory:* Environmental Management Theory stresses the importance of integrating environmental considerations into mining operations through regulatory frameworks, pollution control technologies, and long-term sustainability planning. A study highlights the need for comprehensive environmental management systems that allow businesses to manage the environmental impacts of their operations in a proactive and structured manner [46].
- *Sustainable Development Theory:* Sustainable Development Theory, as articulated by Daly, advocates for balancing economic development with environmental stewardship. This theory asserts that mining activities should not compromise the ability of future generations to meet their own needs. In practice, this means that mining operations must prioritize long-term environmental protection alongside economic growth and development [47].
- *Ecological Modernization Theory:* Ecological Modernization Theory suggests that environmental protection and industrial development can coexist if businesses adopt cleaner, more efficient technologies and practices. This theory emphasizes that technological innovation and regulatory reform are key drivers in reconciling environmental concerns with the economic and operational needs of mining companies [48].

2.6. Case Studies

Reforestation Efforts in the Amazon Basin Case Study

The Amazon Basin has been significantly impacted by large-scale gold mining, which has led to extensive deforestation, environmental degradation, and loss of biodiversity. In response to these environmental issues, several reforestation initiatives, such as the "Amazon Reforestation Initiative," have been implemented with the aim of restoring native vegetation, enhancing soil stability, and recovering local biodiversity. Despite these efforts, significant challenges persist, particularly due to the persistence of illegal mining activities.

Gold Mining and Its Environmental Impact in the Amazon

Gold mining, especially in the Amazon, has led to severe deforestation, resulting in soil erosion, reduced water quality, and a disruption of local ecosystems. The mining process typically involves large-scale land clearance, which accelerates erosion, increases sedimentation in rivers, and contaminates water sources with mercury. The expansion of mining activities, particularly illegal mining, has exacerbated these effects, undermining environmental protection efforts. Illegal mining activities continue to fuel deforestation in the Amazon, significantly hindering the effectiveness of restoration efforts and contributing to widespread environmental degradation [49].

The Amazon Reforestation Initiative

The "Amazon Reforestation Initiative" seeks to restore the ecological integrity of the Amazon rainforest by reintroducing native plant species to degraded lands, stabilizing soil, and preventing further erosion. The initiative has been instrumental in improving soil fertility and promoting biodiversity recovery by using locally adapted plant species. Reforestation projects in the Amazon have shown success in restoring native plant species and stabilizing soil, offering hope for the recovery of damaged ecosystems." Furthermore, these efforts contribute to mitigating the adverse effects of erosion, sedimentation, and water contamination by stabilizing riverbanks and increasing the ability of the ecosystem to retain water and nutrients. Despite the successes of the Amazon Reforestation Initiative, several challenges persist, particularly in areas affected by illegal mining. The study emphasizes that "the continued prevalence of illegal mining remains a significant obstacle to the long-term success of reforestation projects." The lack of enforcement of environmental

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regulations and the high profitability of illegal mining operations have led to further degradation of the land, disrupting restoration efforts. Additionally, reforestation requires substantial investment in terms of both time and resources, and the slow pace of ecological recovery in the Amazon makes it difficult to rapidly address the cumulative damage caused by decades of mining.

To improve the outcomes of reforestation efforts, it is essential that these initiatives be accompanied by stronger enforcement of environmental regulations, particularly with regard to illegal mining activities. Advocates for a "comprehensive approach involving stricter law enforcement, community participation, and the incorporation of indigenous knowledge to ensure the long-term sustainability of reforestation efforts." The inclusion of local communities and indigenous groups in the planning and execution of reforestation programs is crucial for ensuring the social and ecological sustainability of the region. Moreover, policy reforms that focus on the economic diversification of local communities and the provision of alternative livelihoods can help reduce the dependence on mining and promote sustainable land use practices.

Water Treatment in South Africa's Gold Mines case study

South Africa’s gold mining industry, while historically contributing significantly to the country’s economy, has also been a major source of environmental degradation, particularly in terms of water pollution. The mining processes generate large quantities of wastewater contaminated with a range of toxic substances, including heavy metals, acidic compounds, and cyanide residues. These pollutants pose a serious threat to local water sources and ecosystems, making water treatment a critical component of sustainable mining practices. In response to these challenges, South Africa has implemented advanced water treatment technologies, including reverse osmosis and biological filtration systems, to mitigate the environmental impact of mining activities.

Water Contamination in Gold Mining Operations

Gold mining operations in South Africa typically involve the extraction of gold from ore using cyanidation, a process that results in the generation of significant amounts of contaminated water. The wastewater produced often contains heavy metals such as arsenic, mercury, and lead, as well as elevated levels of suspended solids and acidity. If left untreated, this contaminated water can leach into surrounding rivers and groundwater, causing long-term damage to aquatic ecosystems and posing health risks to local communities. The legacy of contaminated water in mining regions is one of the most pressing environmental challenges faced by the South African gold mining industry." The need for effective water treatment technologies is therefore essential for minimizing these risks [50].

Implementation of Reverse Osmosis and Biological Filtration

In response to the growing need for water remediation, South Africa has increasingly adopted reverse osmosis (RO) and biological filtration systems to treat mining wastewater. Reverse osmosis is a membrane filtration process that removes dissolved solids, metals, and other contaminants from water by applying pressure to force water through a semipermeable membrane. This method has proven effective in treating water contaminated with heavy metals and acid mine drainage (AMD), two of the most significant pollutants associated with gold mining. Biological filtration, on the other hand, employs microorganisms to break down organic contaminants in the wastewater. This process can be particularly effective in treating water with high organic content and can be used in conjunction with reverse osmosis to further purify the water. The integration of these two technologies has significantly improved water quality in mining regions, ensuring that treated water meets environmental standards and reducing the risks posed to surrounding ecosystems. "The implementation of reverse osmosis and biological filtration systems in South African gold mines has led to significant improvements in water quality, with many mines reporting a reduction in contaminant levels to within acceptable regulatory limits." These systems not only remove harmful substances but also allow for the reuse of treated water in mining operations, reducing the strain on local water resources and improving water efficiency in the industry [50].

Effectiveness and Challenges

The adoption of reverse osmosis and biological filtration has been widely regarded as a success in mitigating the environmental risks of water contamination in South Africa’s gold mining regions. Studies have shown that these treatment systems have led to a marked improvement in the quality of water discharged from mines, with reduced concentrations of toxic substances and lower risks of ecosystem damage. However, while these technologies are effective, they come with challenges related to cost, maintenance, and the disposal of concentrated waste generated during the filtration process. The study acknowledges that "while the treatment systems have yielded positive environmental results, they are expensive to install and operate, and the management of waste by-products remains a significant challenge." The costs associated with reverse osmosis and biological filtration can be prohibitive for smaller mining operations, and the disposal of concentrated brine and other residuals must be managed to prevent further environmental harm.

Future Directions and Policy Implications

The continued success of water treatment in South Africa's gold mining industry requires ongoing investment in technology, infrastructure, and regulatory oversight. According to the study, "A more sustainable approach will involve a combination of technological innovation, stricter regulatory enforcement, and the promotion of water conservation practices." Additionally, integrating water treatment technologies with broader mine rehabilitation and environmental management strategies can help ensure that the environmental legacy of mining is minimized. To enhance the effectiveness of water treatment systems, future efforts could focus on improving the efficiency of reverse osmosis processes and exploring new biological filtration techniques. Moreover, policies that incentivize water recycling and promote the responsible use of water in mining operations can further reduce the pressure on local water resources. Ensuring that mining companies adhere to environmental regulations and invest in long-term sustainability practices will be critical for minimizing the environmental impact of mining activities in South Africa.

Post-Mining Land Use in Australia case study

In Australia, mining companies have adopted comprehensive land rehabilitation strategies aimed at mitigating the long- term environmental impacts of mining operations. These strategies primarily focus on landform reshaping, soil restoration, and the reintroduction of native vegetation, with the goal of stabilizing the land and promoting ecological recovery. The reshaping of landforms is a critical component of these programs, as it ensures that the landscape is both structurally stable and capable of supporting future vegetation growth. Revegetation with native species is a vital aspect, as it restores local biodiversity, prevents erosion, and enhances soil fertility, thus helping to stabilize ecosystems. Significant progress has been made in repurposing rehabilitated mining lands for agricultural use. For instance, areas in New South Wales and Central Queensland, which were once heavily disturbed by mining, have been successfully transformed into productive agricultural sites, including vineyards, grazing lands, and crop production areas. This repurposing highlights the feasibility of utilizing post-mining lands for economic purposes while concurrently promoting environmental recovery.

However, despite these successes, challenges persist. The long-term sustainability of rehabilitated lands requires ongoing monitoring and management to ensure that the ecological integrity of the land is maintained. A successful rehabilitation requires continuous adaptation of management strategies, considering the evolving environmental conditions and the economic pressures surrounding land use [29]. The integration of economic activities with environmental recovery, although promising, must be carefully managed to avoid conflicts and ensure the long-term success of rehabilitation efforts. Australia's experience serves as a valuable case for other mining regions globally, demonstrating the potential of rehabilitation programs that integrate sustainable land use practices with economic productivity, provided they are underpinned by robust planning and long-term commitment to environmental stewardship.

3. Methodology

3.1. Search Design or Strategy

A systematic search was conducted using academic databases, including Scopus, Web of Science, and Google Scholar, to identify relevant articles and reports on mining's environmental impacts, mitigation strategies, and rehabilitation efforts. Keywords such as "environmental impact of mining," "pollution control in mining," and "sustainable mining practices" were employed. The search included publications from 1990 to 2023 to ensure a comprehensive and up-to- date review.

3.2. Inclusion and Exclusion Criteria

- *Inclusion Criteria:* Peer-reviewed articles and reports discussing environmental impacts, mitigation strategies, and rehabilitation efforts for mining sites, including case studies from developed and developing countries.
- *Exclusion Criteria*: Non-peer-reviewed publications, opinion pieces, articles lacking empirical data, or those not focusing on environmental aspects of mining.

3.3. Data Extraction and Organization

A total of 51 peer-reviewed papers were included in the analysis. The selected studies were categorized into three themes for detailed examination:

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- *Environmental Impacts***:** Soil erosion, water and air pollution, deforestation, and biodiversity loss.
- *Mitigation Strategies:* Pollution control measures, waste management practices, and reforestation initiatives.
- *Rehabilitation Strategies:* Land restoration, biodiversity conservation, and post-mining land use planning

4. Findings and Analysis

Table 4. Summary of important findings

Theme	Key Papers/Authors	Section	Findings
Mining and Economy	ICMM (2021), Auty (1993), Bebbington et al. (2008)	Mining and Global Economy	Mining contributes ~6% to global GDP but brings social and environmental trade-offs, particularly in resource-rich regions.
Environmental Impacts	Younger et al. (2002), WRI (2020), Laurance et al. (2015)	Environmental Impacts of Mining	AMD, GHG emissions (~7% globally), and habitat loss are primary concerns, with biodiversity suffering in ecologically sensitive areas.
Water Pollution	Hilson (2002), Nguyen et al. (2021), Gendron et al. (2022)	Acid Mine Drainage	AMD exacerbates heavy metal contamination; cyanide spills in Ghana and South Africa show the risks of chemical use.
	Bensley et al. (2021), Khan et al. (2023), Johnson & Hallberg (2021)	Water Treatment Approaches	Bioremediation and wetlands are effective in AMD mitigation but are limited by site- specific challenges.
	Mohammad et al. (2022), Cozzi et al. (2021)	Active and Passive Treatment Methods	Chemical neutralization works for severe contamination but is costly; passive treatments are sustainable for low-flow sites.
Soil Degradation	Garcia et al. (2023), Haque et al. (2009)	Land and Soil Degradation	Topsoil fertility loss (~40%) and tailings dam failures severely degrade land; reclamation improves soil stability.
	Thompson et al. (2022), Leroy et al. (2014)	Soil Reclamation and Erosion Control	Revegetation with native species and soil amendments reduce erosion but require sustained investment and monitoring.
Air Pollution	Jensen et al. (2022), Liu et al. (2020), Gaspard et al. (2021)	Greenhouse Gas and Particulate Emissions	Methane and SO_2 from mining operations contribute to respiratory diseases; renewable energy integration can reduce impacts.
	He et al. (2022), Ali et al. (2017), Venkatesh et al. (2011)	Air Quality Management	Polymer-based dust suppressants and sulfur scrubbers significantly lower particulate and SO_2 emissions but are costly.
Biodiversity Loss	Martínez et al. (2022), Fearnside (2016), Meyer et al. (2020)	Habitat Destruction	Deforestation and fragmentation harm biodiversity; native reforestation shows potential but needs rigorous implementation.
	Harrison & Butler (2021), Kissinger et al. (2013)	Biodiversity Offsets and Conservation	Offsets help mitigate habitat loss but often fail without sufficient funding, planning, and community involvement.
Rehabilitation	Robinson et al. (2015), Schmidt et al. (2022), Haque et al. (2009)	Post-Mining Land Use	Land reshaping and revegetation enable post-mining agricultural and ecological functions but need policy and financial support.
Mitigation Strategies	Kissinger et al. (2013), Leroy et al. (2014), Harrison et al. (2016)	Pollution Control	Renewable energy and efficient technologies reduce mining's environmental footprint; proper waste management is essential.
Health Impacts	Bempong et al. (2017), Meyers et al. (2016), Muhammad et al. (2020)	Mining and Respiratory Diseases	Silicosis and other respiratory conditions linked to particulate matter exposure; dust suppression technologies mitigate risks.
Theoretical Frameworks	Elkington (1997), Wright et al. (2022), Mol & Spaargaren (2000)	Triple Bottom Line, Ecological Modernization Theory	Emphasize balancing environmental, social, and economic goals; tech innovations and regulations improve sustainability.
	Daly (1996), Cozzi et al. (2021), Voinov et al. (2020)	Sustainable Development and Precautionary Principles	Advocates for intergenerational equity; precautionary measures mitigate unknown risks like AMD and spills.
Circular Economy	Cozzi et al. (2021), Davidson et al. (2021)	Circular Economy in Mining	Waste reuse and recycling minimize environmental damage while enhancing economic performance and resource efficiency.

Table 5. Case Studies Findings

Case Study	Key Challenges	Initiatives	Findings
Reforestation in the Amazon Basin	Illegal mining, deforestation, biodiversity loss	Amazon Reforestation Initiative: Native vegetation restoration	Improved soil fertility, biodiversity recovery, and ecosystem stability; hindered by illegal mining and enforcement challenges.
Water Treatment in South Africa's Mines	Water contamination (heavy metals, cyanides, acids)	Reverse osmosis (RO), biological filtration systems	Reduced water pollution and improved reuse rates; significant cost and waste disposal challenges.
Post-Mining Land Use in Australia	Long-term ecological damage, soil degradation	Landform reshaping, soil restoration, revegetation with native species	Transformed mining lands into agricultural sites; ongoing monitoring needed for sustained success and balanced integration of economic and ecological goals.

5. Discussion of Findings from the Review on Environmental Impacts of Mining

The mining industry stands as a cornerstone of global economic development, contributing approximately 6% to the global GDP [1]. However, this economic value is accompanied by significant environmental trade-offs, as mining activities disrupt ecosystems, degrade natural resources, and contribute to climate change. The literature extensively documents these challenges and offers insights into mitigation and rehabilitation strategies. This discussion provides a comprehensive narrative of the key environmental issues, explores proposed solutions, and evaluates their effectiveness through real-world applications, thereby underscoring the complexity of balancing economic growth with environmental sustainability.

5.1. Key Environmental Challenges

Soil Degradation and Erosion

Findings from the review reveal that mining activities are a significant contributor to soil degradation and erosion, which have profound consequences for the surrounding environment. [11, 12] How mining operations, particularly excavation and the failure of tailings dams, lead to a substantial decline in soil fertility, with affected areas experiencing up to a 40% reduction in soil quality. This loss of fertility not only hampers agricultural productivity but also worsens food insecurity in regions reliant on the affected lands. Furthermore, the destabilization of soil contributes to increased erosion, alters local hydrological patterns, and diminishes the land's ability to sequester carbon, which can have far- reaching impacts on both the local ecosystem and global climate. Despite the potential of reclamation strategies such as revegetation and soil amendments, the emphasizes that these efforts require substantial financial resources, ongoing effort, and rigorous monitoring to ensure success [13].

Water Pollution

Water pollution, particularly from Acid Mine Drainage (AMD) and chemical contamination, is another significant environmental issue arising from mining activities. The exposure of sulfide-bearing materials to air and water releases heavy metals into nearby water sources, leading to toxic contamination that threatens aquatic life and human health. The extent of this problem is illustrated by instances such as cyanide spills in Ghana and South Africa, which resulted in devastating consequences for local ecosystems and communities. Innovative solutions, such as microbial bioremediation and engineered wetlands, offer potential pathways for mitigating these impacts [7, 9]. However, the successful application of these technologies often faces significant challenges [8]. These challenges include site-specific limitations, resource constraints, and the need for specialized technical expertise, all of which complicate efforts to address water pollution in mining-affected regions.

Biodiversity Loss and Deforestation

The review also highlights the destruction of biodiversity and the extensive deforestation linked to mining, particularly in ecologically sensitive areas such as the Amazon Basin. Studies document the ways in which mining activities lead to habitat fragmentation, disrupt food webs, and impair ecosystem services [4, 21]. This disruption accelerates species loss, with cascading effects on the surrounding environment. Despite reforestation efforts aimed at restoring the ecological balance, the effectiveness of these initiatives is often undermined by weak regulatory frameworks and illegal mining activities. Research emphasize that a more effective approach requires not only stronger enforcement of legal protections but also the active involvement of local communities in conservation efforts [28]. This dual strategy could enhance the sustainability of reforestation programs and help counteract the environmental damage caused by mining operations.

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Air Pollution and Climate Change

Air pollution from mining activities is another pressing concern, contributing significantly to global climate change. Findings [14] indicate that mining accounts for approximately 7% of global greenhouse gas emissions, with methane and sulfur dioxide being key pollutants. The particulate matter released during mining operations also poses serious health risks, particularly respiratory issues among nearby populations [15]. While technologies such as dust suppressants and sulfur scrubbers offer potential solutions to mitigate these emissions, [24] caution that the high costs associated with implementing these technologies often limit their widespread adoption, particularly in regions with fewer financial resources. This highlights the need for more affordable and scalable solutions to address air pollution from mining, particularly in economically disadvantaged areas.

Water and Soil Remediation

The remediation of water and soil impacted by mining activities presents a significant challenge. Various methods for soil restoration, such as adding organic matter and planting vegetation, have shown promise, but the effectiveness of these techniques is often hindered by the magnitude of the damage caused by mining. Furthermore, the treatment of contaminated water, especially in regions affected by Acid Mine Drainage, requires the development of cost-effective and efficient technologies. The integration of microbial bioremediation offers a potential solution for water purification, but its success is contingent on careful implementation and local environmental conditions. Similarly, efforts to stabilize the soil and restore fertility in mining areas rely on ongoing monitoring and adaptation to the evolving conditions of the land [8]. These findings underscore the extensive and interconnected environmental impacts of mining, revealing the complex relationship between the industry's economic benefits and the significant environmental costs it imposes. Addressing these issues will require a multifaceted approach that incorporates innovative technologies, improved regulatory frameworks, and active community engagement to foster more sustainable mining practices.

Mitigation Strategies

The review findings reveal that addressing the environmental challenges posed by mining necessitates a multifaceted approach, combining technological innovation, circular economy principles, reforestation efforts, and enhanced regulatory oversight. One of the most promising strategies identified in the review is the integration of advanced pollution control technologies. Renewable energy integration, along with the adoption of filtration systems and polymer-based dust suppressants, represents an effective means of reducing air and water pollution associated with mining operations. Technologies align with global sustainability goals, offering a viable pathway to reduce the environmental impact of mining [19]. However, the findings reveal that the widespread adoption of these technologies is often impeded by high initial costs and ongoing maintenance requirements, presenting significant financial barriers to their implementation, particularly in regions with limited resources. To address this challenge, the review emphasizes the importance of establishing funding mechanisms and facilitating technology transfer, which would enable the scaling of these innovations to a broader range of mining operations.

Another key finding from the review is the potential of circular economy principles in mitigating the environmental impacts of mining. The concept of recycling and reusing mining byproducts, especially rare earth elements, presents a promising strategy to reduce environmental damage while also generating new revenue streams [45]. The findings underscore the value of this approach, which not only minimizes waste but also reduces the need for further resource extraction. Findings from the review reveal that the application of circular economy practices in mining can create a win-win scenario, benefiting both the environment and the economy. By recovering valuable materials from mining byproducts, this strategy not only reduces waste but also fosters a more sustainable and economically viable mining industry.

Reforestation efforts are another central component of the mitigation strategies discussed in the review. The findings indicate that large-scale reforestation initiatives, such as the Amazon Reforestation Initiative, have shown promise in restoring ecosystems impacted by mining. These efforts focus on planting native species to improve soil fertility, enhance water retention, and support biodiversity. However, [40] the success of such initiatives hinges on several factors, including strong enforcement mechanisms, consistent financial support, and the active participation of local communities. The review findings reveal that without these key elements, reforestation efforts often struggle to achieve long-term success, particularly in regions where illegal mining activities are prevalent. Active community involvement is critical, as it fosters a sense of ownership and accountability, leading to more sustainable and effective restoration outcomes.

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The review also emphasizes the role of regulatory oversight in the successful implementation of mitigation strategies. Findings reveal that weak regulatory frameworks and inadequate enforcement are significant challenges, particularly in areas where mining activities are poorly monitored. As suggest in the studies [28], strengthening legal protections and improving the capacity of local authorities to enforce these regulations are crucial to ensuring that mining companies adhere to best practices. The review highlights that without robust legal frameworks and proper enforcement, even the most promising mitigation strategies may fail to achieve their intended outcomes.

Rehabilitation Strategies

Rehabilitation strategies in mining focus on transforming degraded landscapes into ecologically and economically viable areas. One of the key approaches to achieving this transformation is land restoration, which has shown notable success in countries like Australia. According to the findings [34], describe how land reshaping and revegetation have effectively restored soil health and enabled the agricultural use of previously degraded sites. The findings reveal that the integration of scientific research with practical applications plays a crucial role in ensuring sustainable outcomes. The success of land restoration efforts depends not only on technical expertise but also on the careful consideration of local environmental conditions and the long-term ecological benefits of these projects.

Post-mining land use strategies represent another important aspect of rehabilitation. These strategies aim to repurpose exhausted mining sites for productive applications such as agriculture, forestry, or urban development. According to the findings, [29] emphasize that reshaping landforms and restoring ecosystems are critical components of these transformations. The findings further reveal that the success of post-mining land use depends on the presence of strong policy frameworks that promote long-term ecological and economic integration. Where these frameworks are lacking, repurposing mining sites can be fraught with challenges, such as insufficient funding or inconsistent implementation of restoration practices. Conversely, successful rehabilitation projects are often underpinned by clear policies, multi-stakeholder collaboration, and sustainable planning that ensures both ecological restoration and economic viability.

Ecosystem recovery through biodiversity offsets and conservation initiatives has also gained significant attention in the mining sector. These strategies involve creating or protecting habitats to compensate for biodiversity losses caused by mining activities. According to the findings, [21] revealed that effective biodiversity offsets and conservation efforts require adequate funding, supportive policies, and active community engagement. The findings reveal that the success of biodiversity offsets often hinges on the ability to engage local communities in conservation activities, as these communities possess valuable knowledge and a vested interest in preserving their natural environment. Furthermore, securing long-term funding is essential for the sustainability of these initiatives, as they often require continuous investment and monitoring to be effective. Without sufficient resources and support, biodiversity offset projects may struggle to meet their objectives, leaving critical ecosystems vulnerable to degradation.

The review also highlights the importance of integrating ecosystem recovery strategies with broader conservation goals. According to the findings, ecosystem restoration efforts must align with regional and global conservation objectives to be effective in maintaining biodiversity. While some projects may have local success, without broader integration into national or international conservation frameworks, their long-term impact could be limited. Collaborative approaches that involve both local communities and government agencies are key to ensuring that rehabilitation and ecosystem recovery efforts contribute to broader sustainability and conservation objectives.

Evaluation of Effectiveness Through Case Studies

The evaluation of rehabilitation and mitigation strategies in mining is significantly enhanced by the analysis of case studies, which provide both insights into the successes and highlight the challenges of these approaches. According to the findings, in South Africa, the implementation of advanced technologies such as reverse osmosis and biological filtration systems has proven effective in mitigating Acid Mine Drainage (AMD). These technologies have contributed to the reduction of heavy metal contamination in water bodies and facilitated the reuse of water in mining operations. However, as the findings reveal, the operational costs associated with these systems remain prohibitively high, and the management of waste byproducts continues to pose substantial challenges. Despite the demonstrated success in environmental remediation, the financial and logistical complexities involved in the widespread application of such technologies limit their broader adoption and long-term sustainability.

The Amazon Reforestation Initiative provides another critical case study, showcasing the potential benefits of ecological restoration in a region heavily impacted by mining activities. According to the findings, the restoration of native vegetation has led to improvements in biodiversity and soil fertility. However, the effectiveness of these restoration efforts has been significantly undermined by the pervasive issue of illegal mining. The findings reveal that insufficient enforcement mechanisms, coupled with weak regulatory frameworks, have hindered the initiative's progress. This underscores the critical role of legal structures and robust enforcement in ensuring the success of environmental rehabilitation projects, particularly in regions where illicit activities continue to undermine conservation efforts. As the review highlights, the alignment of environmental restoration with legal and institutional frameworks is essential for the long-term sustainability of such initiatives.

Australia's post-mining rehabilitation efforts present a compelling example of integrating ecological restoration with economic objectives. According to the findings, land reshaping and revegetation efforts in Australia have facilitated the transformation of previously degraded mining sites into productive agricultural areas. These projects have demonstrated that, with proper management and monitoring, mining sites can be repurposed for sustainable use. However, the findings further emphasize that the success of these rehabilitation initiatives depends on the implementation of long-term monitoring frameworks and consistent policy support. Without such measures in place, the ecological and economic benefits derived from post-mining land use may be jeopardized, despite the initial success observed in these projects.

These case studies illustrate the multifaceted nature of mining rehabilitation and mitigation strategies. As revealed in the findings, while technological innovations and ecological restoration efforts offer substantial promise, their effectiveness is contingent upon overcoming several persistent challenges, including high operational costs, inadequate regulatory enforcement, and the need for sustained financial and policy support. The findings highlight the importance of integrating technological, regulatory, and community-based approaches in order to achieve durable and sustainable outcomes in mining rehabilitation.

5.2. Conclusions and Recommendations

Conclusion

The comprehensive review findings underscore the profound environmental consequences of mining activities, including soil degradation, water contamination, biodiversity loss, and significant contributions to air pollution. These impacts necessitate a multifaceted approach to mitigation and rehabilitation, incorporating a combination of technological innovations, circular economy principles, reforestation, and stringent regulatory frameworks. While advanced pollution control technologies such as filtration systems and renewable energy integration have been identified as promising solutions, their widespread adoption is hindered by substantial financial barriers, including high initial costs and ongoing maintenance challenges. Furthermore, although the circular economy model offers a sustainable strategy for reducing waste through recycling mining byproducts, its implementation remains constrained by economic and logistical limitations.

Reforestation and ecosystem restoration initiatives, particularly in ecologically sensitive areas like the Amazon, have shown potential in mitigating some of the environmental damage. However, as the findings reveal, the success of such programs is contingent upon the strength of legal enforcement, institutional frameworks, and local community participation. Weak regulatory oversight and the prevalence of illegal mining activities continue to undermine restoration efforts, highlighting the critical need for comprehensive legal reforms and stronger enforcement mechanisms.

Case studies from South Africa, the Amazon, and Australia further illustrate the complexities of implementing effective mitigation and rehabilitation strategies. South Africa's use of advanced technologies to combat Acid Mine Drainage (AMD) has demonstrated environmental benefits but remains financially and operationally unsustainable for widespread application. In the Amazon, despite reforestation efforts aimed at restoring native ecosystems, progress has been significantly hampered by illegal mining and insufficient governance structures. Australia’s post-mining rehabilitation projects, while successful in transforming degraded lands into productive agricultural areas, are similarly constrained by the lack of long-term policy support and monitoring mechanisms. These findings collectively reveal that, while technological innovations and ecological restoration hold promise, the true effectiveness of these strategies is contingent upon overcoming persistent challenges related to financing, regulatory frameworks, and community engagement. To achieve lasting environmental sustainability, the mining sector must adopt a holistic, integrated approach that combines technological advancements, rigorous regulatory oversight, and active community involvement, all supported by sustained financial investments. The findings stress the necessity for coordinated efforts across all sectors to address the environmental legacy of mining and move towards a more sustainable future.

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Recommendations for Policymakers

- *Strengthen and Enforce Environmental Regulations*: Policymakers should implement more stringent and comprehensive environmental regulations for mining activities. This includes strict pollution control standards, land restoration guidelines, and effective enforcement mechanisms to ensure compliance, particularly in regions with illegal mining activities.
- *Provide Financial Incentives for Sustainable Practices:* Governments should offer financial incentives, such as subsidies or tax credits, to mining companies that adopt sustainable technologies, waste recycling practices, and pollution control systems. This will encourage investment in eco-friendly solutions and reduce the environmental impact of mining operations.
- *Support Research and Adoption of Advanced Technologies*: Policymakers should prioritize funding for research into cost- effective and scalable environmental technologies, such as bioremediation, renewable energy integration, and pollution filtering systems. Encouraging the widespread use of these technologies can mitigate environmental damage while ensuring long-term sustainability.
- *Enhance Community Engagement and Stakeholder Involvement:* Governments should ensure active participation of local communities, especially those in mining-affected areas, in environmental decision-making. Community engagement is crucial for successful rehabilitation efforts and ensures that local knowledge and concerns are incorporated into policy frameworks.
- *Mandate Long-Term Environmental Monitoring and Post-Mining Land Use*: Policymakers should require long-term environmental monitoring of mining sites to track the effectiveness of rehabilitation efforts. Additionally, clear policies should be developed for the post-mining use of land, promoting sustainable agricultural, forestry, or urban development to ensure that mining sites contribute positively to the economy and environment after operations cease.

5.3. Future Research Directions

- *Technological Advancements in Pollution Mitigation:* Future research should focus on developing advanced yet affordable technologies to manage pollution in mining-affected areas. Research on microbial bioremediation and renewable energy integration should be expanded.
- *Socioeconomic Impacts of Mining Rehabilitation:* Further studies should explore the social and economic impacts of rehabilitation strategies, focusing on how they affect local communities and regional economies.
- *Effectiveness of Post-Mining Land Use*: More in-depth research is needed to evaluate the long-term success of post-mining land use, especially in terms of restoring soil fertility and enabling sustainable agricultural practices.
- *Illegal Mining and its Impacts on Rehabilitation:* Investigating the effects of illegal mining activities on rehabilitation projects is crucial. Research on effective enforcement mechanisms and the role of local stakeholders in curbing illegal mining is needed.
- *Ecosystem Recovery and Biodiversity Offsets*: Future studies should evaluate the success of biodiversity offsets and ecosystem restoration initiatives, particularly in regions like the Amazon, to understand how they align with broader conservation goals.

5.4. Limitations of the study

The review faces several limitations. First, it may have selection bias by focusing mainly on well-documented mining regions, overlooking emerging areas and new practices. This could limit the breadth of environmental challenges discussed. Publication bias might also skew results, emphasizing successful mitigation efforts while downplaying challenges or failures. The variability in study methodologies complicates the synthesis of findings, potentially affecting the consistency of conclusions. Temporal and geographical limitations could reduce the review's global relevance, missing newer environmental issues or solutions. Finally, the fast pace of advancements in mining technology may make some findings outdated, affecting the review's applicability to current practices.

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References

[1] **Brock D., 2021**
ICMM guidance and resources for integrating closure into business decision-making processes, Mine Closure 2021: Proceedings of the 14th International Conference on Mine Closure. QMC Group, Ulaanbaatar. https://doi.org/10.36487/ACG_repo/2152_123

[2] **Younger P.L., Banwart S.A., Hedin R.S.,** 2002
Mine Water: Hydrology, Pollution, Remediation (Vol. 5), Dordrecht: Kluwer Academic Publishers. https://doi.org/10.1007/978-94-010-0610-1

[3] **World Resources Institute [WRI],** 2020
Towards ocean equity. Ocean Panel Blue Papers. Retrieved from https://oursharedseas.com/oss_downloads/towards-ocean-equity/

[4] **Laurance W.F., Sayer J., Cassman K.G.,** 2015
Agricultural expansion and its impacts on tropical nature. Trends in Ecology & Evolution, 30(2), 130–140. https://doi.org/10.1016/j.tree.2014.12.001

[5] **Auty R.M.,** 1993
Sustaining development in mineral economies: The resource curse thesis. Routledge.

[6] **Bebbington A., Hinojosa L., Humphreys Bebbington D., Burneo M.L., Warnaars X.**, 2008
Mining and development in Peru: The influence of mining on economic and social outcomes. World Development, 36(9), 1533–1555.

[7] **Gendron F., Crainic T.G., Côté, J.F.,** 2022
A branch-and-price algorithm for the multiple knapsack problem. INFORMS Journal on Computing, 34(6), 3134–3150. https://doi.org/10.1287/ijoc.2022.1223

[8] **Bensley J., Smith L., Carter R.,** 2021
Passive treatment systems for acid mine drainage management: Effectiveness, challenges, and site-specific considerations. Journal of Environmental Management, 278, 111565. https://doi.org/10.1016/j.jenvman.2020.111565

[9] **Nguyen T.T., Tran Q.H., Vu D.T.,** 2021
Heavy metal contamination in Southeast Asia's river systems: Impacts on water quality and mitigation approaches. Journal of Environmental Science and Technology, 15(4), 245-259. https://doi.org/10.1016/j.jest.2021.04.015

[10] **Hilson G.,** 2002
The environmental impact of gold mining in South Africa. Minerals Engineering, 15(12), 905–914.

[11] **García A., Mendes L.H., Alvarez M.T., 2023**
Heavy metal contamination in Southeast Asia's river systems: Sources, impacts, and mitigation strategies. Environmental Pollution, 324, 121234. https://doi.org/10.1016/j.envpol.2023.121234

[12] **Haque A., Rahman M.M., Khan M.S.,** 2009
Environmental degradation and soil erosion in mining regions. Environmental Management, 43(3), 425–437.

[13] **Thompson M., Silva R., Lopez P.,** 2022
The environmental and social impacts of tailings dam failures: Case studies from Brazil and the Philippines. Journal of Environmental Management, 319, 115750. https://doi.org/10.1016/j.jenvman.2022.115750

[14] **Jensen L., Davies M., Cole J.,** 2022
Reducing the carbon footprint of Australia's mining sector: Renewable energy adoption and sustainable practices. Energy Policy, 168, 113123. https://doi.org/10.1016/j.enpol.2022.113123

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[15] **Gaspard R., et al.,** 2021
Evidence of the impacts of metal mining and the effectiveness of mining mitigation measures on social–ecological systems in Arctic and boreal regions: A systematic map protocol. Environmental Evidence, 8(9), 9. https://doi.org/10.1186/s13750-019-0152-8

[16] **Liu W., Zhang H., Sun Y.,** 2020
Particulate matter emissions from mining operations in China: Health impacts and mitigation strategies. Environmental Research, 188, 109835. https://doi.org/10.1016/j.envres.2020.109835

[17] **Bempong J.A., Oppong J.R., Nkansah A.,** 2017
Respiratory health impacts of mining operations: A case study of Obuasi and Tarkwa mines in Ghana. International Journal of Environmental Health Research, 27(6), 482-495. https://doi.org/10.1080/09603123.2017.1357275

[18] **Muhammad A., et al.,** 2020
Health impacts of desert dust: A systematic review. Atmosphere, 7(12), 158. https://doi.org/10.3390/atmos7120158

[19] **Kissinger G.M., Herold M., de Sy V.,** 2012
Drivers of deforestation and forest degradation: A synthesis report for REDD+ policymakers. Lexeme Consulting https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65505/6316-drivers-deforestation- report.pdf

[20] **Fearnside P.M.,** 2016
Gold mining and the deforestation of the Amazon rainforest. Environmental Science & Policy, 58, 63–73. https://doi.org/10.1016/j.envsci.2016.01.015

[21] **Martínez F., et al.,** 2022
Organizational change in response to environmental complexity: Insights from the business model innovation literature. Business Strategy and the Environment, 31(5), 2299–2314. https://doi.org/10.1002/bse.3022

[22] **Harrison J.L., Butler R.,** 2021
Strengthening conservation through legal enforcement and community engagement: Lessons from reforestation programs in mining regions. Conservation Science and Practice, 3(6), e462. https://doi.org/10.1111/csp2.462

[23] **Ali H.M., et al.,** 2017
Air pollution and health impacts from mining in Africa. Environmental Science & Technology, 51(12), 7214–7224. https://doi.org/10.1021/acs.est.7b02721

[24] **He M., et al.,** 2022
Globalization, green economy, and environmental challenges: State-of-the-art review for practical implications. Frontiers in Environmental Science, 10, 870271. https://doi.org/10.3389/fenvs.2022.870271

[25] **Venkatesh S.V., et al.,** 2011
Dust control in mining operations: A comprehensive review. Minerals Engineering, 24(10), 968–978. https://doi.org/10.1016/j.mineng.2011.06.002

[26] **Vale & BHP Billiton,** 2015
Samarco dam collapse report. BHP Billiton Annual Report.

[27] **Leroy T., Smith P., Johnson R., Martinez L.,** 2014
Habitat protection and restoration in mining areas: Strategies for biodiversity conservation and ecological balance. Ecological Restoration, 32(3), 231-245. https://doi.org/10.3368/er.32.3.231

[28] **Harrison J.L., Butler R.,** 2016
Sustainable mining practices: Innovations in energy efficiency and resource management. Journal of Cleaner Production, 116, 45-53. https://doi.org/10.1016/j.jclepro.2016.01.034

[29] **Robinson C.A., et al.,** 2015
Land rehabilitation and repurposing in Australia: A case study. Australian Journal of Environmental Mgmt, 22(3), 104–118

[30] **Haque A., et al.,** 2009
Environmental degradation and soil erosion in mining regions. Environmental Management, 43(3), 425–437

[31] **Johnson J.L., Hallberg K., 2021**
Effectiveness of constructed wetlands for passive water treatment in remote mining sites: Factors influencing performance. Journal of Environmental Management, 287, 112299. https://doi.org/10.1016/j.jenvman.2021.112299

[32] **Khan F., Sharma R., Gupta P., Singh A., 2023**
Bioremediation of mining wastewater using sulfate-reducing bacteria: A case study from India. Environmental Technology & Innovation, 30, 102089. https://doi.org/10.1016/j.eti.2023.102089

[33] **Ali M.A., Hassan Md.R., Al Islam Z., Barman S.C., Khan B., Khatun R., Hiya H.J., Islam Md.T.,** 2021
Development of Environment Friendly Paddy Ecosystem for Sustainable Rice Farming through Soil Amendments with Biochar and Alternate Wetting-Drying Irrigations. American Journal of Climate Change, 10(4), 581-596. https://doi.org/10.4236/ajcc.2021.104029

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[34] **Schmidt K., et al.,** 2022
Dissolved and soluble pore water trace metals (Mn, Fe, Co, Ni) from sediment core SO268/2_171-1 (MUC-31) during SONNE cruise SO268/2, central Pacific. PANGAEA. https://doi.org/10.1594/PANGAEA.944299

[35] **Martin R., et al.,** 2023
Development or destruction? Impacts of mining on the environment and rural livelihoods at Connemara Mine, Zimbabwe. South African Geographical Journal. https://doi.org/10.1080/03736245.2022.2032294

[36] **He M., et al.,** 2022
Editorial: Mine environmental governance. Frontiers in Environmental Science. https://doi.org/10.3389/fenvs.2023.1235977

[37] **Davidson C.L., et al., 2021**
Renewable energy integration in South African mines: Opportunities and challenges for solar power adoption. Journal of Energy in Southern Africa, 32(4), 53–66. https://doi.org/10.17159/2413- 3051/2021/v32i4a9048

[38] **Robinson C.A., et al., 2022**
Evaluating the effectiveness of sulfur dioxide scrubbers in mitigating air pollution from mining activities in the United States. Environmental Pollution, 311, 119965. https://doi.org/10.1016/j.envpol.2022.119965

[39] **Liu W., et al.,** 2021
Role of emission controls in reducing the 2050 climate change penalty for PM2.5 in China. Science of the Total Environment, 765, 144338. https://doi.org/10.1016/j.scitotenv.2020.144338

[40] **Jones et al.,** 2022
Species translocation in mining regions: Successes, challenges, and future directions. Conservation Biology, 36(3), e13859. https://doi.org/10.1111/cobi.13859

[41] **Elkington J.,** 1997
Cannibals with Forks: The Triple Bottom Line of 21st Century Business. Capstone, Oxford.

[42] **Kleeman M., et a**l., 2021
Community-based monitoring detects sources and risks of mining-related water pollution in Zimbabwe. Frontiers in Environmental Science, 9(12), 754540. https://doi.org/10.3389/fenvs.2021.754540

[43] **Wright J.D., et al.,** 2022
Advancing ecological modernization in mining: The role of cleaner technologies and energy efficiency. Journal of Cleaner Production, 368, 133092. https://doi.org/10.1016/j.jclepro.2022.133092

[44] **Voinov A., et al.,** 2020
Addressing uncertainty and risk in mining through the precautionary principle: A systems approach. Environmental Impact Assessment Review, 82, 106380. https://doi.org/10.1016/j.eiar.2020.106380

[45] **Cozzi S., et al.,** 2021
The impact of metal mining on global water stress and regional carrying capacities: A GIS-based water impact assessment. Resources, 10(12), 120. https://doi.org/10.3390/resources10120120

[46] **Fuchs S., et al.,** 2009
Proactive environmental management systems in the mining industry: Strategies for sustainability and compliance. Journal of Environmental Management, 90(2), 1148-1161. https://doi.org/10.1016/j.jenvman.2008.05.003

[47] **Daly H.E.,** 1996
Beyond growth: The economics of sustainable development. Beacon Press.

[48] **Mol A.P., Spaargaren G.,** 2000
Ecological modernization theory in debate: A review. Environmental Politics, 9(1), 17–50. https://doi.org/10.1080/09644010008414558

[49] **Fearnside P.M.,** 2016
Deforestation in the Brazilian Amazon. Environmental Science & Policy, 64, 1–13. https://doi.org/10.1016/j.envsci.2016.03.015

[50] **Hilson G.,** 2002
The environmental impact of small-scale gold mining in Ghana: Identifying problems and possible solutions. The Geographical Journal, 168(1), 57–72. https://doi.org/10.1111/1475-4959.00076