Indian Journal of Geography and Earth Sciences *Volume 01, Issue 01 March 2026, pp. 52-67*

Environmental and ecological risks in mining: A comprehensive analysis of issues and options for mitigation and rehabilitation

Rajeev Kumar[1], Pardeep Kumar[2], Mahendra Phulwaria[3] and Mukesh Kumar[4]

[1]Professor, Department of Geography, Govt. College Bahadurgarh, Jhajjar, Haryana

[2] Faculty, Department of Geography, Govt. College Bahadurgarh, Jhajjar, Haryana

[3] Faculty, Department of Botany, Govt. College Bahadurgarh, Jhajjar, Haryana

[4] Scientist D, Ministry of Environment, Forest and Climate Change, Indira Paryavaran Bhawan, New Delhi, India

Abstract

Mining activities have played a pivotal role in global economic development but are often associated with significant environmental challenges. This study critically examines the environmental impact of mining operations and evaluates various management strategies and rehabilitation techniques employed to mitigate these effects. The assessment encompasses a broad spectrum of mining-related environmental concerns, including soil degradation, water pollution, deforestation, biodiversity loss, and air quality degradation. The first section of the study provides an overview of the diverse environmental impacts associated with mining activities, highlighting the complexities and interdependencies of these issues. Following this, a comprehensive examination of current management strategies is presented, focusing on regulatory frameworks, sustainable practices, and technological advancements aimed at minimizing negative environmental consequences. The study emphasizes the importance of adopting a holistic and integrated approach that considers the unique characteristics of each mining operation and the ecosystems it affects. Furthermore, the discussion delves into rehabilitation techniques designed to restore ecosystems impacted by mining activities. This includes the exploration of ecological restoration methodologies, such as reforestation, wetland restoration, and soil stabilization, as well as innovative approaches involving the use of native plant species and soil amendments. The effectiveness of these techniques in promoting sustainable landscapes and fostering biodiversity recovery is evaluated based on case studies and empirical evidence. This study highlights the imperative for a proactive and adaptive approach to address the environmental challenges posed by mining activities. The synthesis of effective management strategies and rehabilitation techniques is essential to strike a balance between economic development and ecological preservation. Future research directions are proposed, emphasizing the need for collaborative efforts among stakeholders, continued technological innovation, and the integration of sustainable practices into mining industry operations. Ultimately, this study aims to contribute to the ongoing global discourse on achieving responsible and sustainable mining practices.

Keywords: Ecological Risk, Mining, Mitigation, Rehabilitation, Phytostabilization

Introduction

The process of extracting valuable minerals and resources from the Earth, known as mining, has been essential to the development of human civilization, industry, and technological advancements. Given that it accounts for about 6% of the world's GDP, the mining industry is crucial to contemporary economic systems. (1). Air pollution is another important way that mining affects the environment. A significant portion of methane emissions, which have a 25-fold greater potential for global warming than carbon dioxide, are produced by coal mining alone, accounting for around 7% of global greenhouse gas emissions [3]. The impacts are made worse by smelting, which releases sulfur dioxide and heavy metals that cause acid rain and put people around at risk for breathing problems. Mining-related environmental damage also causes species loss, deforestation, habitat fragmentation, and species extinctions, which are putting important ecosystem services like soil fertility, carbon storage, and water purification at danger [4]. The loss of biodiversity puts the environment at risk in the long term and makes ecological imbalances worse.

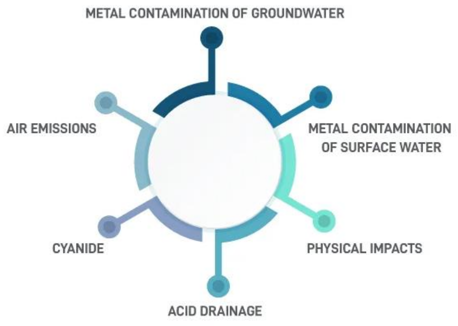
The environmental impacts of mining are further exacerbated by its social dimensions. Although mining activities contribute to infrastructure development and employment generation. he concept of sustainable mining has emerged as a framework to reconcile the social, environmental, and economic dimensions of mining in response to these challenges. Rehabilitating degraded ecosystems, promoting circular economy principles, and integrating environmentally sustainable extraction technologies are all essential elements of responsible mining practices. Utilizing advanced water treatment technologies to mitigate acid mine drainage, reforesting and reestablishing native vegetation to rehabilitate mined lands, and integrating renewable energy sources into mining operations are some prominent strategies. A thorough evaluation of the environmental impact of mining is essential, considering the industry's ongoing dependence on it to sustain global economic development.

Research Issue and Justification

A lot of research has been done on the environmental effects of mining, but there is still a lack of understanding of how to best reduce and repair damage in specific situations. Furthermore, a multitude of techniques are available, although their efficacy fluctuates based on geographical context, mining type, and enforcement procedures. This paper fills a gap in research by closely examining the environmental problems that come with mining, looking at both the problems and the ways to fix them.

Environmental Impacts of Mining

Mining is necessary to get the raw materials that are needed for progress in technology and industry. Mining, on the other hand, can do a lot of damage to the environment, which can have big effects on air, water, soil, and biodiversity. This part looks at the most important environmental problems that come up when mining. It uses the most recent research and literature to understand how big these problems are and suggest ways to make them less serious (Figures 1 and 2).



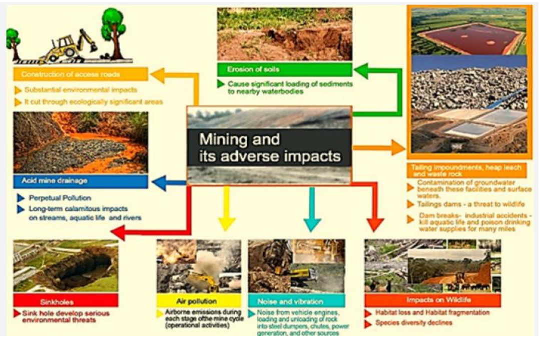


Fig.1. Special Environmental impacts of mining **Fig. 2**. Ecological impacts of mining

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

Mining operations release greenhouse gases (GHGs), sulfur dioxide (SO_2), and particulate matter (PM) into the air, which is bad for the environment and people's health. Key processes, like digging, moving, and processing minerals, produce carbon dioxide (CO_2) and methane (CH_4). Methane, which is a byproduct of coal mining, is a very strong greenhouse gas (GHG) that may warm the planet 25 times more than CO_2. Mining activities together make up about 7% of all greenhouse gas emissions in the world. When sulfur-containing ores are smelted, they release sulfur dioxide, which causes acid rain and damage to the environment. SO_2 can also be bad for your health because it can make breathing problems worse, including asthma. Particulate matter from digging, blasting, and moving things around also includes fine particles (PM2.5) that can get into the lungs and cause serious health concerns, such as heart disease.

Using renewable energy, technologies to capture methane, sulfur capture systems like flue gas desulfurization, and dust suppression techniques are all ways to reduce the effects of climate change. These steps, together with strict rules, are necessary to lower air pollution and encourage more environmentally friendly mining methods. The authors suggest switching to renewable energy sources like solar and wind power to cut down on the use of fossil fuels and lessen the damage mining does to the ecosystem (Fig.3 [14].

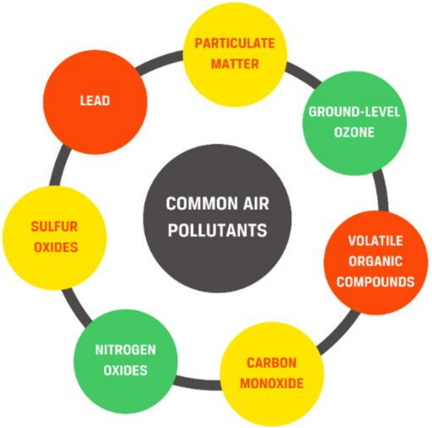


Fig. 3. A graphical representation of common air pollutants

Biodiversity Loss: Habitat Destruction and Ecosystem Disruption

Mining activities cause a lot of biodiversity loss by destroying habitats, breaking up ecosystems, and polluting the environment. When mining companies clear large areas of land and cut down trees, they often move animals and plants that live there (Fig 4 & 5). This destruction of habitats throws off the balance of ecosystems, which lowers the number of species and puts endemic and endangered species at risk of extinction. Mining infrastructure, like roads and pits, breaks up ecosystems, which makes it harder for wildlife to find food and mates. This can lead to genetic bottlenecks. Additionally, mining-related pollution, such as the release of heavy metals, sedimentation, and acid mine drainage, poisons plants and animals and contaminates soil and water bodies, which has a huge impact on aquatic ecosystems. The combined effects of these disruptions weaken ecosystem services like cleaning water, storing carbon, and making soil fertile. This makes environmental damage worse and makes it take longer and more difficult for ecosystems to recover. [19]. Also, mining damages the soil, which makes it harder for carbon to be stored, making the environmental impact even worse. Reforestation and ecosystem restoration can help lessen these effects, but it can take a long time—sometimes decades—for carbon sequestration functions to come back. The study shows how important it is to have strong forest protection measures and sustainable mining practices to fight climate change.

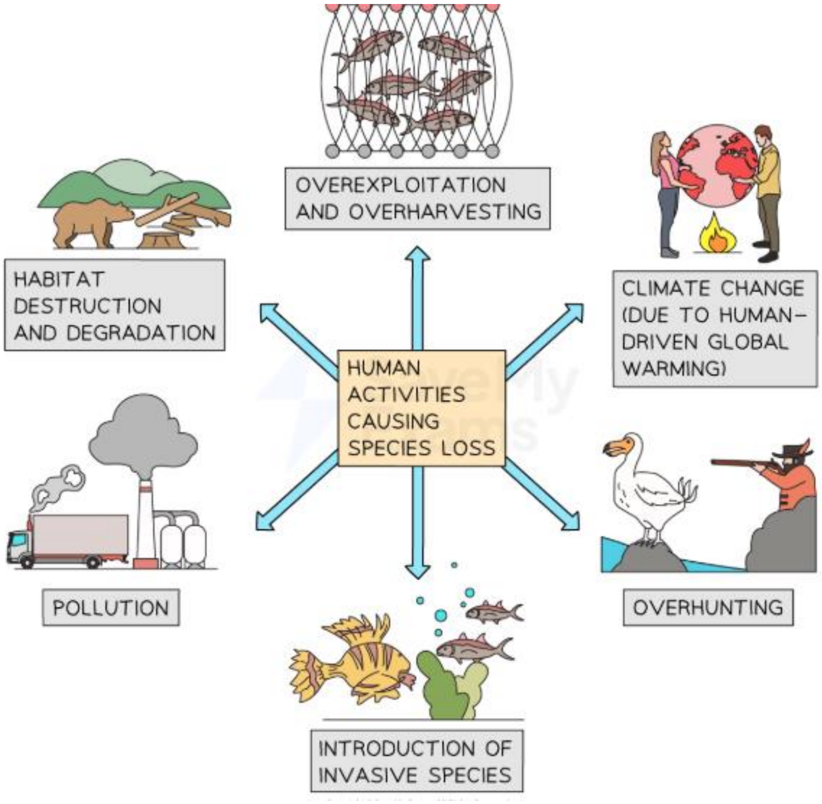


Fig. 4. Anthropogenic activities cause loss of biodiversity

Fig. 5 A view of cutting down of tree plantation in forest areas

Table 1. Key facts on how mining affects the environment

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 ommunities.
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.

Mitigation and Rehabilitation Strategies for Mining Activities

Mining has a big effect on the environment, including water, soil, air, and biodiversity. To solve these problems, we need to have good strategies for mitigation and rehabilitation. The goal of these strategies is to reduce the damage to the environment that mining does (mitigation) and to restore ecosystems after mining stops (rehabilitation).

Mitigation Strategies

Mitigation strategies focus on pollution control, habitat restoration, and responsible waste management to reduce or stop environmental damage during mining operations. Important steps to reduce the effects include:

Table 2. Technologies for controlling pollution 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.

Plans for Rehabilitation

Rehabilitation strategies aim to bring mining-affected areas back to a state that supports ecological functions and lets people use the land after mining. These plans are meant to fix the soil, bring back biodiversity, and make land use possible in the future.

- Ecological Restoration
- Reshaping landforms
- Post-Mining Land Use

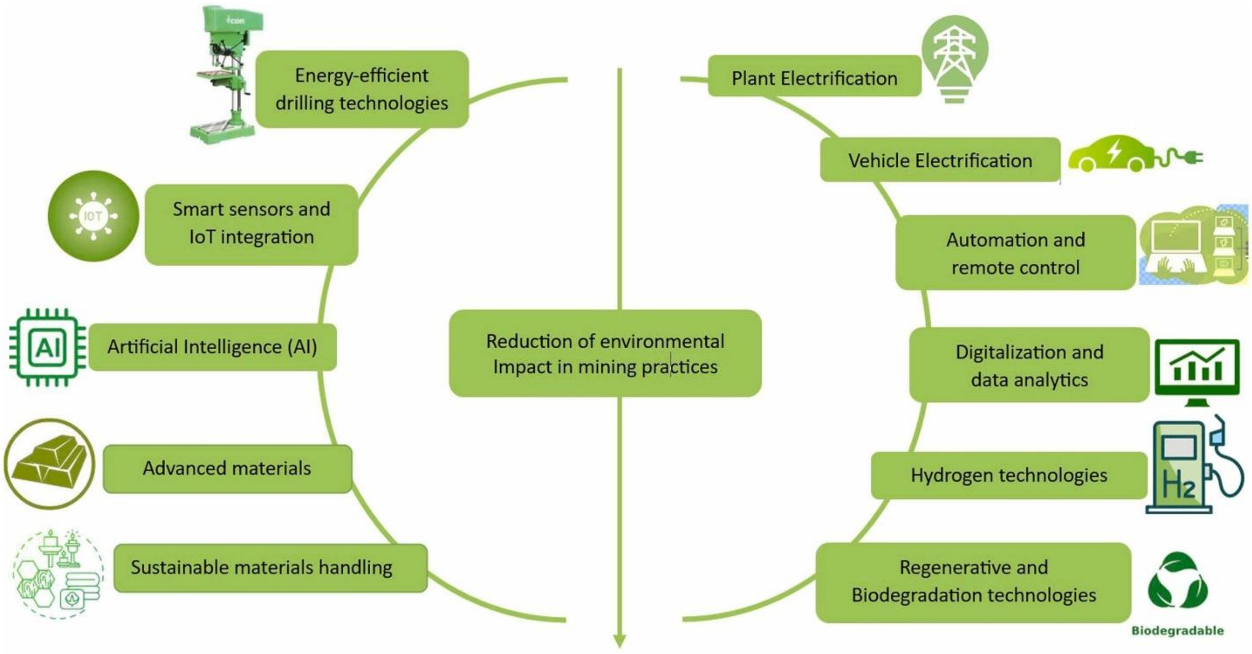


Fig. 6 Introduction of green technology to mitigate mining operations

Rehabilitation of Soil

Mining can cause a lot of damage to soil, such as erosion, loss of fertility, and less ability for plants to grow. For the environment to recover, it is important to restore soil health and stop it from getting worse.

- Soil Amendments: People often use soil amendments like organic matter, lime, and biochar to make the soil healthy again. A study of soil amendment strategies in Central Asia, observing that the incorporation of organic materials such as compost can enhance soil fertility by augmenting microbial activity and facilitating nutrient cycling [33]. Biochar is a type of charcoal made from organic waste. It has gotten a lot of attention because it can improve the structure of soil, hold moisture, and make highly degraded soils more fertile.

- Reforestation and Vegetation Restoration: Reforestation and restoring vegetation are two important ways to stabilize soil, stop erosion, and help the environment recover. A study on the deforestation efforts at coal mining sites in Australia found that planting native plants helped stabilize the soil, stop erosion, and bring back biodiversity [34]. The research shows how important it is to use native plants to make sure that reforestation and soil health recovery work.

- Erosion Control: To stop the soil from getting worse, erosion control is very important, especially in areas where open-pit mining is going on. Silt fences, erosion control blankets, and hydroseeding are all common ways to stop erosion. Hydro seeding is a method where a mixture of seed, water, and mulch is sprayed over the soil. A study on erosion control in African mining sites showed that the best way to stop soil erosion was to use both plants and physical barriers [35].

Control of Air Quality

Mining is a big cause of air pollution, especially dust and small particles, as well as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions. To lessen these effects on the environment, it is important to have good air quality control plans.

- Dust Suppression
- Cleaner Energy Sources
- Technologies for controlling emissions
- Offsets for biodiversity

Moving Species

When habitat destruction is inevitable, species translocation—relocating endangered species to new habitats—can aid in the preservation of biodiversity. A researched translocation initiative in mining areas revealed that, although translocation may achieve short-term success, enduring challenges such as genetic bottlenecks and the establishment of viable populations frequently obstruct long-term efficacy [40]. Their research underscores the need to evaluate genetic diversity and the appropriateness of recipient habitats before initiating translocation initiatives.

Table 3. 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	Effective for immediate results, but expensive, energy-intensive, and requires long-term operation

	remove heavy metals.	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.

Theoretical Framework for Strategies for Mitigation and Rehabilitation

There are a few important theoretical frameworks that can help us understand how well mining's mitigation and restoration measures function. These frameworks stress how important it is to include environmental factors in mining operations and make sure they can last for a long time:

- Environmental Management Theory: This theory says that mining operations should take environmental factors into account by using rules, pollution control technologies, and planning for long-term sustainability. A study shows that businesses need comprehensive environmental management systems that let them control the effects of their operations on the environment in a proactive and organized way [46].

- Sustainable Development Theory: According to Daly, Sustainable Development Theory says that we should find a balance between economic growth and taking care of the environment. This theory says that mining shouldn't make it harder for future generations to meet their own requirements. In practice, this implies that mining companies must put protecting the environment for the long term ahead of making money and growing the economy [47].

- Ecological Modernization Theory: Ecological Modernization Theory posits that environmental conservation and industrial advancement may coexist, provided that enterprises implement cleaner and more efficient technologies and methodologies. This hypothesis says that technology progress and changes to the rules are two of the most important things that can help mining corporations balance their environmental concerns with their business needs [48].

Changing the climate and air pollution

Mining activities that pollute the air are another big problem that is making climate change happen faster around the world. According to findings [14], mining is responsible for about 7% of global greenhouse gas emissions, with methane and sulfur dioxide being the most harmful. The dust and other particles that mining releases are also very bad for your health, especially for people who live nearby [15]. Technologies like dust suppressants and sulfur scrubbers could help lower these emissions, but [24] warns that the high costs of using these technologies often make it hard for many people to use them, especially in places where money is tight. This shows that we need cheaper and more scalable ways to deal with air pollution from mining, especially in areas with low incomes.

Fixing the soil and water

It is very hard to clean up water and soil that have been damaged by mining. Different ways to restore soil, like adding organic matter and planting plants, have worked in the past, but the damage done by mining is often too much for these methods to work. Additionally, treating polluted water, especially in areas affected by Acid Mine Drainage, needs the creation of technologies that are both cheap and effective. Integrating microbial bioremediation could be a way to clean up water, but it will only work if it is done carefully and the right environmental conditions are present. In the same way, efforts to stabilize the soil and make mining areas fertile again depend on ongoing monitoring and adjusting to the changing conditions of the land [8].

Strategies for Lessening the Impact

The study shows that dealing with the environmental problems caused by mining requires a multi-pronged approach that includes new technologies, circular economy principles, reforestation efforts, and better regulatory oversight. This study found that combining advanced pollution control technologies is one of the most promising strategies. The use of filtration systems and polymer-based dust suppressants, along with the integration of renewable energy, is a good way to cut down on the air and water pollution that comes from mining. Technologies are in line with global goals for sustainability, and they offer a good way to lessen the environmental effects of mining [19].

Reforestation is another important part of the strategies for reducing damage that were talked about in this study. The results show that big reforestation projects, like the Amazon Reforestation Initiative, have worked to restore ecosystems that mining has hurt. These efforts are focused on planting native plants to make the soil more fertile, hold more water, and support more types of plants and animals [40].

This study also stresses how important it is for regulators to keep an eye on things in order for mitigation strategies to work. The results show that weak regulatory frameworks and poor enforcement are big problems, especially in places where mining activities aren't well monitored. As the studies [28] suggest, it is very important to make legal protections stronger and give local governments more power to enforce these rules in order to make sure that mining companies follow best practices. The study underscores that, in the absence of robust legal frameworks and effective enforcement, even the most promising mitigation strategies may not realize their intended objectives.

Prospects for Further Research

- Technological Developments in Pollution Mitigation: Future studies should concentrate on creating cutting-edge yet reasonably priced technology to control pollution in regions impacted by mining. More research should be done on the integration of renewable energy sources and microbial bioremediation.
- The social and economic effects of rehabilitation techniques should be investigated further, with an emphasis on how they impact regional economies and local communities.
- The long-term viability of post-mining land use, particularly with regard to recovering soil fertility and facilitating sustainable farming methods, requires further investigation.
- The consequences of illegal mining activities on rehabilitation efforts are an important topic to research. It is necessary to conduct research on the role of local stakeholders in preventing illegal mining as well as efficient enforcement strategies.
- Ecosystem Recovery and Biodiversity Offsets: Future research should assess the effectiveness of ecosystem restoration and biodiversity offsets, especially in areas like the Amazon, to determine how they fit with more general conservation objectives.

Research constraints

The main indicators usually include things like mine resources, the environment, social factors, and economic factors. Secondary indicators are things like vegetation cover, waste emissions, landscape patterns, topography, mine development, and hydro-climatic conditions. Tertiary indicators give more information about things like geological hazards, how the landscape is broken up, the physicochemical properties of plants, the characteristics of the soil, the water bodies, and the density of the population.33–35. Right now, research on ecological environmental evaluation indicator systems for mining areas is mostly focused on these areas: indicator systems for figuring out how much mine resources can hold, how vulnerable mining areas are to ecological damage, how safe mines are for the environment, and how healthy ecosystems are in mining zones.36–38. There are usually a lot of indicators, clear structural hierarchies, and systemic features in the ecological environmental evaluation indicator systems for mining areas.

Main Environmental Issues in 2025

Mining activities in 2025 still have to deal with a lot of ecological problems, some of which are rated as having a "very high" impact:

• Water Contamination and Acid Mine Drainage (AMD): Sulfide minerals release heavy metals like mercury and lead into waterways and groundwater, which is very harmful.
• Huge Amounts of Waste: The world has produced more than 100 billion tonnes of tailings, so dams need to be constantly checked for stability and risk.

- Loss of biodiversity and land degradation: Mining causes up to 7% of the world's deforestation each year. In 2025, strip mining alone is expected to damage 20 to 70 hectares of soil at each site every year.

- Carbon Intensity: The sector is responsible for about 7% of all greenhouse gas emissions in the world. Coal mining is still the most carbon-intensive activity, releasing an estimated 6,000 million tonnes of CO2 every year.

Strategies for fixing technology

To save money and make things more efficient, the industry has moved toward high-tech, "nature-based," and "technology-driven" restoration methods by 2025:

- AI-Powered Restoration: Operators use AI to predict how the environment will change and carefully plan restoration efforts, which could cut carbon footprints by 35% to 55%.
- Advanced Phytoremediation: Using certain plants to stabilize or remove pollutants from the soil.

Modern versions often use nanotechnology, like nanoscale zero-valent iron (nZVI), to make cleaning the soil more effective.

- Bioremediation and Biotransformation: Using microorganisms to break down organic pollutants or change heavy metals into forms that are less harmful.

- Landform Recontouring: Changing the shape of mine sites to improve the health and stability of the soil. This can cut long-term restoration costs by up to 30%.

Practices for Sustainable Extraction

"Green mining" practices are becoming the norm to lessen the damage before repairs are needed:

- Electrification and Automation: Switching to electric fleets and self-driving machines lowers diesel emissions on site and makes operations safer.

- Zero-Waste and Circular Economy: "Urban mining" (recycling materials that are already there) and "zero-waste mining" try to get valuable resources back from tailings and products that are no longer useful.

- Water Management: Mines can recycle and reuse up to 70% of their water by using Zero Liquid Discharge (ZLD) systems.

- Innovative Sourcing: Looking into new ways to mine, like fluidized mining, deep-sea mining, and brine mining, to cut down on the amount of land that needs to be mined.

Regulatory and Economic Structures

Refrences :

1. Brock, D 2021, 'ICMM guidance and resources for integrating closure into business decision making processes', in AB Fourie, M Tibbett & A Sharkuu (eds), *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 Revista Minelor – Mining Revue vol. 31, issue 3 / 2025 ISSN-L 1220-2053 / ISSN 2247-8590 pp. 51-71
15. 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
16. 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
17. Muhammad A., et al., 2020. Health impacts of desert dust: A systematic review. Atmosphere, 7(12), 158. https://doi.org/10.3390/atmos7120158
18. 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
19. 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
20. 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
21. 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
22. 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
23. 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
24. 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
25. Vale & BHP Billiton, 2015. *Samarco dam collapse report*. BHP Billiton Annual Report.

26. 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
27. 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
28. Robinson C.A., et al., 2015. *Land rehabilitation and repurposing in Australia: A case study*. Australian Journal of Environmental Mgmt, 22(3), 104–118
29. Haque A., et al., 2009 *Environmental degradation and soil erosion in mining regions*. Environmental Management, 43(3), 425–437
30. 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
31. 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
32. 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 Revista Minelor – Mining Revue vol. 31, issue 3 / 2025 ISSN-L 1220-2053 / ISSN 2247-8590 pp. 51-71
33. 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
34. 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
35. He M., et al., 2022. *Editorial: Mine environmental governance*. Frontiers in Environmental Science. https://doi.org/10.3389/fenvs.2023.1235977
36. 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

37. 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
38. 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
39. 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
40. Elkington J., 1997 *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Capstone, Oxford.
41. Kleeman M., et al., 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
42. 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
43. 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
44. 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
45. 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
46. Daly H.E., 1996. *Beyond growth: The economics of sustainable development*. Beacon Press.
47. 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
48. 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
49. 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