E3S Web of Conferences **693**, 02006 (2026) https://doi.org/10.1051/e3sconf/202669302006
IPMC 2025

Mining with Microorganisms for Environmental Sustainability and Minerals Bio-Circularity

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Abstract. Mining activities release heavy metals, chemicals, and other toxic pollutants into the environment and pollute soil and water sources, posing threats to human health. The consequence of mining pollution in the environment has a significantly larger impact on the overall ecosystem because of extensive mining activities, industrial production, and inappropriate disposal methods. The application of microorganisms to recover and recycle metals from mine tailings and waste provides a sustainable and circular approach to mining waste management. Mining microorganisms with their metal bio-solubilization ability play a significant role in natural minerals biogeochemical cycling. Assimilating mining waste management with sustainability and financial progress is a foremost revolution in the circular economy. The recovery of precious metals from mining wastes has significant potential, with widespread applications to modern society. The resulting pollution and exposure caused by conventional metal recovery techniques cause major health concerns. Bioleaching is a proven technique for the revitalization of valuable metals and rare earth elements from various sectors, enabling the recovery of metals from low-grade ores, mine tailings, and electronic waste, thereby transforming waste into a resource. In the future, the bioleaching process of utilising microorganisms to transform waste into value-added products must be established as a greener and more sustainable alternative. With advanced bioremediation technology, novel methods will be developed for the remediation, recovery, and recycling of different metal values from mining tailings.

1 Introduction

The heavy reliance on the critical and rare-earth metals due to technological advancement has created dispute in the modern world over mining from the earth crust. Mining also affects many human and animal lives due to the increasing demand for electronics, building to medical devices and innumerable other items. But this need for development has a high price: contamination of the environment [1]. Both ecosystems and human health are seriously threatened by these heavy metals. Lead poisoning damages the neurological system, the brain, and the digestive tract. Deficits in copper and iron are brought on by high zinc levels, which also impair immunity. A proven carcinogen, arsenic damages the nervous system and causes breathing issues. Mercury damages the developing foetus as well as the brain and nerve system. The kidneys and nervous system are all harmed by cadmium. Mining operations have terrible environmental effects in addition to hazards to human health, such as biome damage and biodiversity loss. There must be answers to this enormous problem [2]. To lessen the industry's negative environmental effects, cutting-edge technology for mining, processing, and waste management must be developed and implemented. Protecting the environment and public health requires enforcing stronger laws and making sure that mining operations are closely monitored. Government and public support for environmental protection can be obtained by increasing public knowledge and teaching local people about mining dangers and how to mitigate them. The future of the earth and its people is seriously threatened by the mining sector, even though it is vital to economic growth. Current and future generations will suffer greatly if traditional practices are used and environmental repercussions are ignored [3].

The mining sector is a heavy source of pollution and forms the foundation of the infrastructure and industrial sectors. The energy sector's shift to greener technologies and the expansion of infrastructure brought on by a growing population will cause a considerable increase in demand for metals and non-metals in the upcoming years. According to UNEP's Sustainability. A naturally occurring rock or sediment deposit that includes concentrated minerals is called an ore. The necessary minerals are more concentrated in ore with higher ore grades [4].

For instance, magnetite, which has a total iron content of 68 – 71%, is the best ore for extracting iron. Quarrying, which is synonymous with mining, is mainly related to surface mining activities such as shallow deposit excavation, open-pit, and opencast mines. Its main use is to remove building supplies like gravel and sand. Minerals are extracted using a variety of mining techniques. Commonly employed techniques

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include surface, underground, placer, and in-situ mining. The location of the mineral, the deposit's economic worth, environmental factors, and chemical composition are the main factors to be considered while choosing a mining technique. The mining technique that poses the fewest issues is the most effective for obtaining a specific material [5].

200 tonnes of waste rocks and 110 tonnes of tailings, or waste ore, are produced for every tonne of copper. As a result, a sizable amount of waste is produced by the mining sector, including gaseous wastes from different processing operations, tailings, slag, wastewater and sludge, waste rocks, and overburden. It is emitted from a diversity of foundations and processes, including drilling, blasting, crushing, screening, ore body/ore removal, topsoil removal (during the opening of new mines), and land clearance. Air pollution is also largely caused by the on-site loading and unloading of materials, ore processing, and subsequent off-site transportation [6].

Around the world, groundwater is essential for providing water for various uses, including agriculture, industry, and human use. It is a good choice for areas with limited surface water supplies, especially those that are arid or semi-arid. About 20% of the clean water requirement is met by groundwater, which is the primary source of drinking water in many nations [7]. Therefore, preserving its quality is crucial for the welfare of human populations. Groundwater frequently contains mineral compounds, including fluoride, phosphate, and sulphate, which can be dangerous for drinking water if present in excess. Both the population's health and the health of the intended customers may be impacted by these drugs. The existence of fluoride in underground water sources is a worldwide issue since a sizable portion of the population of the globe endures exposure to water that contains fluoride [8]. Most of the fluoride is found in natural water bodies as unbound ions, usually from the breakdown of minerals such as fluorite (CaF2) in groundwater [9]. In the arid regions of several nations, such as Bangladesh, Nigeria, South Africa, Pakistan, and India, the prevalence of water that is sulphate and phosphate-rich has led to problems. Although the Environmental Protection Agency (EPA) and World Health Organisation (WHO) have approved the acceptable concentration of mineral compounds, surpassing these limits may be dangerous to people. Consumer risks from nitrate, sulphate, fluoride, phosphate, and ammonium have been studied in groundwater in numerous locations worldwide. According to the guidelines established by the Iranian Institute of Standards and Industrial Research, a range of permissible fluoride concentrations in drinking water has been established [10]. Fluoride concentrations must specifically be within the range of 0.6 and 1.6 mg/l, according to the accepted norms. This threshold not only establishes acceptable limits but also emphasises the importance of exercising caution when assessing the fluoride concentration of drinking water. There have been some problems for customers because of exceeding the permitted limit of 1.7 mg/l. Nitrate is frequently present in groundwater and affects its quality due to the large amount of incorporated substance that is versatile in movements, and has longevity in aquatic situations. High consumption of mineral pollutants, including phosphates, fluoride, and sulphate, affects the digestive, endocrine, and psychological systems. It has been demonstrated that nitrate and fluoride can harm infants and cause cancer in addition to other health issues in those who are vulnerable [11]. If the quantities are stronger than what is deemed safe, these chemicals may interact with amines to produce secondary compounds through metabolism that are toxic to humans. Additionally, the combination of mineral contaminants and groundwater microbes may cause additional health issues for vulnerable customers, such as children, pregnant women, and older individuals. The general health of water is evaluated using specific traits of a specific kind of bacteria known as water-soluble measures, or TCs. Due to their rapid reproduction, TCs have the potential to contaminate groundwater, which could affect drinking water. The detrimental effects of TC-contaminated water have been the subject of numerous investigations. To evaluate the health risks to consumers, it could be useful to consider possible associations connecting rehab facilities and mineral impurities, especially in arid or semi-arid areas that rely on outflow and contain mining poisons [12]. Determining the potential effects of waterborne pollution exposure requires methods for evaluating health hazards. By providing a systematic framework for statistically or semi-quantitatively evaluating the adverse effects of meeting potentially dangerous drugs, this methodology facilitates risk assessment across various age groups.

2 Types of Emerging Mining Pollutants Sources

Particulate matter in suspension may be a source of heavy metal emissions. Ore containing heavy metals is crushed throughout the mining process into tiny fragments that can be discharged into the environment and settle there. Heavy metal-containing suspended particles are released into the atmosphere because of drilling operations and explosions [13]. Because sulfuric acid-containing sediments and acidic mine drainage contaminate surface and subsurface waters, mining operations are often the cause of water contamination. Water contamination can also result from rainfall and runoff carrying heavy metal-contaminated soil and minerals into surface and subterranean water sources. The land surrounding mining sites may also become contaminated by the collection and disposal of heavy metal-containing mineral tailings. The land surrounding the factory may become contaminated because of suspended particles that contain heavy metals that are discharged into the atmosphere. Underground extraction techniques are less polluting than open techniques [14]. Higher heavy metal concentrations in minerals increase the risk of contamination. The discharge of toxic heavy metals can also be affected by the kind of mineralization and the metal content of the ore. Due to the absence of contemporary pollution control technology, older mines frequently produce greater pollutants. Heavy metals may be released into the environment because of the erosion of accumulated mineral tailings. Mines may emit more heavy metals in desert and windy areas because of the lower humidity and vegetation. Tailings with high sulphide content may result in drainage of acids and heavy metal leaks [15].

One of the main ways that manufacturing and processing activities contaminate soil is by the release of heavy metals. Nickel, mercury, lead, aluminium, and zinc, lead, and arsenic are among the pollutants that frequently contaminate groundwater close to mines and smelting facilities, which are where metals like lead and zinc are produced. For instance, if lead-acid batteries, which are commonly found in cars, are disposed of incorrectly, metal may be expelled into the environment. Like this, waste products from industrial procedures like galvanising have high concentrations of cadmium and zinc [16].

Due to industrial operations, several hazardous metals, such as zinc ore, arsenic from, and mercury, are regularly discharged into the atmosphere. During dry and moist deposition, these elements settle into soil surfaces rather than remaining in the atmosphere indefinitely. They accumulate over time and offer direction for a significant environmental risk. Reducing the adverse effects of this atmospheric deposition requires an understanding of the factors affecting it. Metal mining, trash incineration, the cooling down of copper and zinc, and the manufacture of zinc oxide are some of the biggest offenders [17]. Numerous heavy metals are present in substantial amounts in their emissions. Increased condensation in the atmosphere and consequent soil pollution in nearby locations are the immediate results of this. Some locations still have legacy pollution because of this previous dependency. It is essential to comprehend these characteristics to evaluate vulnerability and anticipate possible hazards. A big part is played by weather patterns, including wind direction and precipitation. Deposition patterns far from the initial emission source can be impacted by wind carrying heavy metals over great distances.

3 Pathways of Pollutant Dispersal in the Environment

Depending on the processes involved, industrial activities are known to produce fine particulate matter (PM) that varies in size, shape, and chemical makeup. Metal mining operations are anticipated to develop globally because of the clean energy transition's increased global consumption of certain metals. There is a serious risk to human health because mining operations are known to release small particles that include hazardous metals into the atmosphere [18]. However, because of their diverse chemical composition, generation method, air longevity, dispersion, and environmental fate, it is difficult to characterize and evaluate the effects of these chemicals on living organisms as well as on the biome. Numerous serious health consequences, such as lung cancer, stroke, respiratory infections, and cardiovascular disorders, have been connected to particle pollution exposure. Toxic heavy metals included in dust and airborne aerosols are known to originate from both active and closed mining areas. To turn the heavy metals scattered throughout the ore into materials that can be sold, several processes are carried out throughout the extraction and mineral processing phases, such as blasting, crushing, and grinding of the extracted ores [19]. Large volumes of dust produced by mining operations have the potential to expose local homes and employees to elevated metal(loid) concentrations. One of the biggest occupational hazards is dust from mining activities, particularly when fine material is produced, which has an impact on the environment, human health, and safety. Numerous evaluations have examined various facets of mineral dust, including its sources, mitigation strategies, and monitoring methods. This is especially important when it comes to dust emissions from underground mines and environmental contamination from the pyrometallurgical processing of copper [20]. The significance of metal and metalloid transportation by airborne dust and aerosols released during mining activities in comparison to other transportation pathways including soil, water, and biodiversity. At several mining locations in the Zambian Copperbelt, the effects of gaseous precursors, dust, and atmospheric aerosols, including crystalline silica and metalloids, have also been noted.

Resources of non-ferrous metal minerals are essential and crucial to economic growth. There has been a significant production of mining waste rock because of the exploitation of mineral resources [21]. This indicates that a significant amount of mining waste and waste rocks will be produced, even though some of them may be used as resources. Acid mine drainage (MD) will result from the weathered oxidation of these wastes if environmental regulations are not strictly enforced. Lead-zinc minerals are significant non-ferrous metal mineral deposits that are primarily found in southern China, specifically in the provinces of Fujian, Hunan, and Yunnan. In Pb-Zn mine sites, Cr, Cu, Ni, and Zn are typically found in the toxic metalloid. pollution [22]. For instance, it is simpler for finer tailings to oxidise and release poisonous metalloids because they have a wider contact surface than waste rocks with coarser features. Many researchers have investigated the environmental risk, mobility, and safe disposal of tailings since they have a higher propensity than waste rocks to produce harmful metalloids. However, they discovered that waste rocks were typically ignored and kept in open areas, and tailings were frequently placed in ponds to stop seepage in most mining sites [23].

4 Environmental Impacts of Emerging Mining Pollutants:

Industrial processes that contaminate soil that contains a potent combination of polluted heavy metals, like metal mining, smelting Pb and Zn, and disposing of hazardous waste, represent a significant environmental risk. Beyond lead and zinc, this toxic legacy also includes arsenic, cadmium, and mercury, each of which poses distinct risks to the stability of ecosystems and the health of soil. Cadmium is known to interfere with vital plant functions and build up in edible components, which puts both human and animal health at serious risk. Arsenic is dangerous to the biome and human body because it can change the physiology of plants and poison the food chain [24]. Mercury is harmful to humans because it bioaccumulates in aquatic species and contaminates seafood. The effects of this metal assault go beyond harm to the surface; they penetrate deeply into the soil and interfere with essential ecological functions. Microbial communities are disturbed, affecting soil fertility and nutrient cycling, and plant development is reduced, threatening agricultural productivity and biodiversity. We can use several different methods. There are several types, such as Analysis of 1. Soil Nutrients: By regularly monitoring levels of heavy metals and essential minerals like potassium, phosphorus, and nitrogen, we can detect any nutrient deficiencies caused by metal relationships to plant uptake systems. Monitoring pH values can provide insight into the impact of metal contamination on soil chemistry. Plant growth Analysis: Monitoring indicators like plant height, plant matter, and yield provide unmistakable evidence of the detrimental effects of elements like arsenic, copper, and mercury on crops, as well as the stress and delayed growth caused by heavy metals. The degree of pH variations is also influenced by the type of soil, soils with mixture of sands are more vulnerable than clay soils because of their lower buffering capability [25].

Plants, animals, and people can all be poisoned by heavy metals found in water. Numerous symptoms, including as neurological, gastrointestinal, and respiratory issues, may be experienced by affected individuals. Actions like using water filtration technologies and regulating the use of heavy metals in agriculture and industry are crucial to preventing heavy metal-related water contamination. The information points to a positive correlation between the level of water pollution near the plants and the extent of these heavy metals' pollution of the soil. There is a discernible pattern whereby higher soil pollution levels are associated with higher water pollution levels, and lower soil contamination levels are associated with lower water contamination levels [26]. This link emphasizes how soil pollution may affect water quality and the necessity of efficient remediation techniques to lessen the harmful impacts of heavy metal contamination on the biosphere and human health. When the concentrations of these metals are above tolerance criteria, they build up in the roots together with liquid and other nutrients. Some plants detoxify and remove metals by processes, including deposition onto surfaces or excretion, but, in cases of extreme pollution, metals are transferred to other systems like stems, leaves, and seeds. It is possible to conclude the morphological and biological impacts of soil intoxication on plants [27].

Because heavy metals interfere with the process of photosynthesis, the activity of enzymes, and cell division, plants may exhibit reduced growth and performance. This results in delayed development and, eventually, inferior products from agriculture in terms of quantities as well as quality. Chlorophyll production can be reduced by metal accumulation in plants, which can result in pathogenicity and chlorine poisoning. disturbance of the absorption of nutrients that takes place Certain heavy metals cause imbalances in nutrition in plants by competing with vital minerals including iron, potassium, and magnesium. Reduced photosynthesis, which demonstrates Metals impair electron flow and harm chloroplasts, which lowers photosynthetic efficiency and, in turn, the amount of naturally occurring matter and energy that plants produce. Plant-based metal accumulation has the potential to enter the food supply chain and endanger consumers' health. Water resource contamination is described as Both groundwater and water from surface sources may be impacted by metallic substances from contaminated soil that are carried by rainfall and irrigation. adverse impacts on soil microorganisms, including the breakdown of organic matter and soil fertility are significantly influenced by soil microorganisms [28]. Metal pollution can impact soil fertility and decrease the diversity and activity of these bacteria. According to the findings, these metals can cause chlorosis, necrosis of the leaves, decreased vegetative growth and yield, physiological alterations such as disruption of nutrient uptake and enzyme activity, and heightened vulnerability of greenery to pests and diseases. To mitigate these problems, crop rotation, the control of water, soil restoration, and other strategies, including biological and phytoremediation, are recommended. Plant health and soil conditions can be improved by adjusting the physical properties of the soil, such as pH and the amount of organic matter present [29].

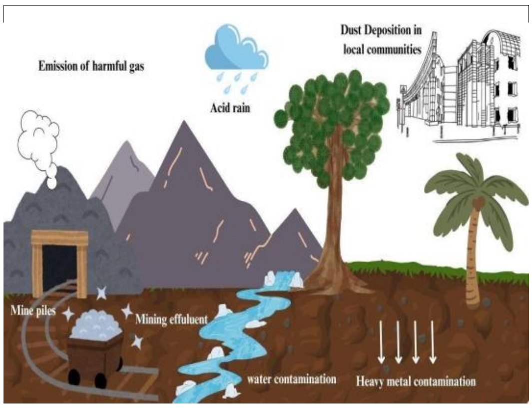

Fig. 1. Describes the environmental impacts of mining activities

5 Human health implications

Substances that are harmful to human health that have entered the environment as a result of human activities are known as environmental contaminants. Environmental contamination can also result from natural events like volcanic eruptions. Human activity releases pollutants into the earth, water, and air. The mouth, food, and breathing are the main ways that pollutants enter the human body. In everyday speech, the term "dose" describes the amount of a certain contaminant that needs to be consumed. The length of exposure and its intensity define the dosage. The degree of exposure can cause a variety of health problems. Even if it contributes to a nation's progress, industrialisation pollutes the environment and damages the health of individuals who are exposed to it [30].

The health of living things is disturbed when they are subjected to soil that has undesirable chemicals or substances in greater quantities than normal. Chemicals used in or generated because of industrial operations, wastewater, residences, livestock, herbicides, and petroleum-derived products are examples of anthropogenic sources of soil contamination. The integration of these chemicals into the soil is largely caused by pesticides and fertilisers, landfills, leaching from organic pollutants, untreated sewage water, and oil spill sludge. Numerous processes, such as incomplete combustion of various materials, smelting, radiological deposition from weapon testing, and nuclear accidents, can result in air deposition. The contemporary era has seen an increase in the manufacture and consumption of plastic [31]. The contemporary era has seen an increase in the manufacture and consumption of plastic. It is typically released into the soil, where it breaks down into a variety of harmful and cancer-causing substances, including toxic heavy metals, bisphenol B, phthalates, dioxins, hydrocarbons that are polycyclic aromatic hydrocarbons, and polychlorinated biphenyls. Exposure to soil contaminated by plastic chemicals increases the risk of heart attack or stroke. Biological pollutants, including pathogens, fungi, viruses, and endocrine disruptors, as well as hormones and medications, are examples of emerging pollutants that have only recently reached atmospheric levels and are usually not monitored. Through the oral, nasal, and epidermal passage these pollutants can enter the human body [32]. Such soil exposure can result in a variety of immediate and long-term, and short-term health issues, including as skin irritation, headaches, coughing, chest pain, and nausea. Individuals who work with dirt regularly or live nearby are vulnerable to inhaling dust particles because they are easily carried by different means and can lead to several health issues. People in several countries have direct touch with soil because it is a part of their tradition to eat it. Youngsters under three are consistently at a higher risk because of their regular contact to soil. Being subjected to heavy metals causes problems with skin contact. Long-term exposure can harm organs and interfere with central nervous system function. Exposure over time may raise the risk of cancer. High contamination levels in the soil generate extremely hazardous crops.

Certain demographic groups are more likely than others to be impacted by pollutants. These show a rise in mortality associated with exposure, mostly to particles and sulphates. Because their biological defences are not as strong as those of the general population, these populations are at risk. Chemical pneumonitis is caused by exposure to cadmium fumes. Epidemiological studies have shown that particulate matter exposure impairs gametogenesis and reduces an individual's capacity for reproduction. Both the quantity and quality of gametes are affected by these. Researchers found a statistically significant association between a statistically significant decrease in conception rates and an increase in traffic-related air pollution in a cross-sectional study using data from a census. There were oligospermia and decreased sperm motility in the semen of some highway toll collectors. Certain pesticide exposure levels increase the risk of birth defects, infertility, spontaneous abortion, sperm abnormalities, and delayed infant development.

Table 1. Health impacts of environmental contamination in various cities.

City	Pollution factor	Pollution	Contact	Symptoms	Precautions	References
Delhi	Traffic, Industry	Pb	Breathing, ingesting	Headache, exhaustion, irritability, memory loss, stomach discomfort, and diarrhoea	Catalytic converters, water treatment, and air filters	(Ryu & Yang, 2018)
Mexico	Industry	Pb	Breathing	Headache, exhaustion, irritability, and memory loss	Purification of drinking water	(Sánchez-Landero et al., 2024)
Seoul	Industry	Hg	Ingesting, breathing	Muscle weakness, tremors, visual issues, Issues with hearing	Mercury exposure and neurological issues	(Chang et al., 2018)
Tokyo	Traffic, industry	Hg	Breathing	Muscle weakness, tremors, visual issues, Issues with hearing	water purification, and air filters	(Kakimoto et al., 2000)
Cairo	Industry	Pb	Breathing	Memory impairment, headache, exhaustion	Using air filters, purifying drinking water,	(Kaunda, 2020)
Mumbai	Traffic, factory	Pb	Ingesting, breathing	Memory impairment, headache, exhaustion, and irritability	Lead exposure, respiratory conditions, and neurological issues	(Patchaiyappan et al., 2021)
Thailand	Agriculture industry	As	Breathing	Aabdominal pain, diarrhoea, vomiting,	Air purifiers	(Kutanan et al., 2015)
Minamata	Chemical factory	Hg	Breathing, ingesting	Muscle weakness, tremors, visual issues, Issues with hearing	Steer clear of eating tainted fish, Water filtration and air filters	(Matsuyama et al., 2021)
Antalya	Tourism industry	Pb	Breathing	Vomiting, diarrhoea, fever, tremors, and nausea	Air filtration and thorough fruit and vegetable washing	(Çoban et al., 2015)
Lanzhou	Coal industry	As	Breathing	Hand and foot numbness and tingling	Washing fruits and vegetables thoroughly	(Liu et al., 2015)
Urumqi	Mining industry	Pb	Breathing, ingesting	Fever, and lack of iron and copper	Air and water purification,	(L. Peng et al., 2020)

6 Mitigation and remediation strategies

Mining waste management is one of the primary concerns about environmental protection and resource efficiency. Innovative and eco-friendly methods are used in mining waste management to address this issue. Using plants that have a high capacity to absorb metals, phytoremediation stabilises heavy metals in soil and water. Utilising nanoparticles as heavy metal adsorbents and separators is known as nanotechnology. using nano membranes to separate and filter water tainted with heavy metals. Chemical techniques: Heavy metals are extracted from mining waste using ionic solvents. applying chemicals to mining waste to stabilise heavy metals. Physical methods: Chemical or water-based washing methods are used to extract heavy metals from mining waste. using substances that are absorbent to adsorb heavy metals from mining waste. using physical, chemical, nano, and biotechnology techniques to improve the efficacy and sustainability of heavy metal-contaminated mining waste management and treatment procedures. creating and implementing cutting-edge, environmentally friendly techniques for the cleanup and management of mining waste while considering the unique circumstances of each site [44]. Reuse and recycling are essential components of contemporary mining operations, demonstrating creative approaches to sustainability. Oils generated from minerals can be purified and reused to reduce their environmental impact and conserve resources. Clean mining water can be used for local irrigation and land rehabilitation. Moreover, adaptive reuse strategies are demonstrated by repurposing abandoned mine tunnels as storage spaces or transit corridors. Advanced technology further supports mining sustainability initiatives. Resource recovery is aided by methods such as hydrometallurgy, which extracts more minerals from ancient tailings. The utilisation of mining materials for 3D printing and the heat generation and treatment of organic matter to produce energy are more examples of the industry's dedication to circularity [45]. Beyond technology, employee involvement and teamwork are crucial. Equipment buyback programs reduce the need to manufacture new equipment while extending the life of existing equipment. Working together with research facilities and academic institutions fosters innovation, which leads to the development of cutting-edge reuse and reclamation technologies. Employee awareness initiatives that support an environmentally conscious culture in mining operations teach employees sustainable behaviours in the interim. Mining operations prioritise energy efficiency and employ a variety of tactics in addition to the usage of renewable energy [46]. This entails putting in place mechanisms to detect and monitor energy consumption across the company, swapping out outdated infrastructure for more energy-efficient models, and switching underground facilities to LED illumination. Employee engagement through initiatives that inform and promote the use of energy-saving techniques is necessary to develop ecological sustainability in mining businesses. Additionally, integrating cutting-edge technology like microgrids, storage batteries, and machine learning helps with energy optimisation and finds possible places where mining operations might save energy. Additionally, using selective membranes to recover metals from liquids requires fewer chemical precipitants.

7 Prospects and obstacles for the future

Soil contaminated with lead, nickel, zinc, and mercury constitutes several of the primary environmental contaminants brought on by the mining industry. The main causes of pollution are mining operations, which include production, processing, waste treatment, and atmospheric accumulation. These pollutants affect soil, water, plants, animals, and people, among other aspects of ecosystem operation and human health. To determine the scope of the issue and develop mitigation and cleanup strategies, efficient pollution monitoring and assessment are required. There are drawbacks to conventional soil remediation techniques, including biological, psychological, and physical processes [47]. Preventing pollution requires analysing innovative techniques and emerging technologies. Sustainable practices and eco-friendly materials are becoming increasingly important for the mineral extraction industry to boost cleanup efforts and lessen its environmental impact. Effective regulation of the metal's titanium, vanadium, nickel, copper, mercury, and other dangerous metals is necessary to guard the environment and human health. Laws and regulations must be implemented to combat the severe harm that pollution around extractive industries causes to the environment and to humans. Stricter environmental regulations must be implemented by governments and regulatory agencies to reduce mining-related pollution. This means simplifying waste management procedures, enhancing oversight and enforcement systems, and putting emission control equipment into place. Funding for studies into cutting-edge approaches to pollution prevention and cleanup must be increased. New techniques to reduce and remove toxicity from vanadium, mercury, nickel, zinc, chromium, and arsenic should be the main emphasis of future research. Evaluating the feasibility and effectiveness of environmental governance and repair strategies in a range of organisational and socioeconomic contexts is necessary to make well-informed judgments about how to manage the environment sustainably.

8 Conclusion

Bioleaching stands as a proven and promising procedure for the sustainable recovery of valuable critical and rare earth elements from secondary resources, electronic waste, and ores, effectively turning waste into a resource. Looking ahead, the integration of advanced bioremediation technologies and microbial processes offers significant potential to enhance metal recovery while minimising environmental impact. As novel methods continue to emerge, bioleaching is poised to become a key component in the development of greener, more efficient strategies for the remediation, recycling, and recovery of metal values across various sectors.

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