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SUSTAINABLE RECLAMATION PRACTICES FOR COPPER TAILINGS DAMS

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ABSTRACT

Mining generates billions of tons of tailings, significantly impacting the environment and society. The disposal of tailings poses significant risks to soil, water, and air quality, making effective treatment crucial for our environment. Adopting sustainable reclamation technologies is necessary to mitigate these negative effects and ensure environmental and economic security. These technologies include chemical stabilization, physical stabilization, biological reclamation, and integrated approaches. The extensive mining of tailings has resulted in considerable environmental and socioeconomic consequences. Addressing these issues requires effective treatment strategies that prioritize sustainable reclamation methods. This review highlights the importance of utilizing advanced technologies, continuous monitoring, community involvement, and robust policy frameworks. Future research should explore innovative cleanup technologies, integrate circular economy principles, and enhance resilience to climate change. These sustainable reclamation strategies offer the potential to mitigate environmental damage, support resource recovery, and improve the quality of life of affected communities.

INTRODUCTION

Since the Stone Age, around 1150 million tons of heavy metals such as copper, lead, cobalt, zinc, cadmium, and chromium have been extracted. It is currently estimated that the yearly worldwide production of mine tailings ranges from 5 to 7 billion tonnes. Mine tailings are composed of residual fine-grained (1-600 mm) pulverized rock left behind after valuable minerals have been removed from the mined ore. They also include process water, which contains dissolved metals and chemicals used in ore processing. In the process of copper mining, the remaining materials known as tailings may make up a significant proportion, ranging from 95% to 99% of the crushed and ground ores. Over the last 10 years, the mining industry has faced challenges such as lower quality ore, the extraction of more difficult ores, higher grinding intensity, and changes in processing technology. Consequently, there has been a substantial increase in the quantity of waste material, referred to as tailings, generated for each unit of ore removed. Consequently, there has been an increase in scrutiny and supervision from both non-governmental organizations and governmental agencies (Edraki et al., 2014).

SUSTAINABLE RECLAMATION

Sustainable reclamation techniques lie in their ability to protect the environment, ensure economic viability, and meet social responsibilities. The following are the key aspects that highlight the importance of sustainable reclamation (Figure 1):

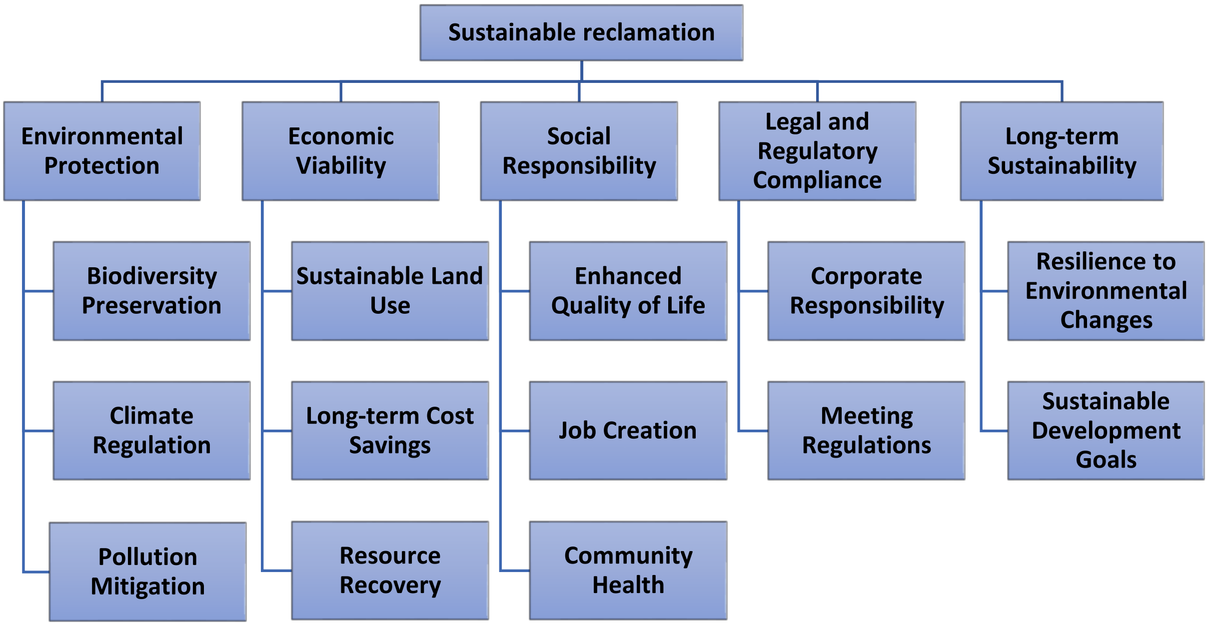

Figure- 1: Importance of sustainable reclamation.

A. Environmental Protection

a. Biodiversity Preservation

Ensuring sustainable reclamation is crucial for the rebuilding of natural habitats and ecosystems, hence promoting biodiversity and protecting endangered species. By reintroducing native plants and creating suitable habitats, these strategies help maintain ecological balance and support a variety of species that depend on certain circumstances (Salgueiro et al., 2020).

b. Pollution Mitigation

Sustainable reclamation employs methods such as botanical remediation and soil stabilization to reduce contamination resulting from hazardous waste. Phytoremediation utilizes plants to absorb harmful substances from soil and water, while soil stability prevents erosion and the spread of contaminants (Sinha et al., 2007). Implementing these measures is essential for mitigating water and soil pollution, ensuring the preservation of cleaner and safer ecosystems for both human and animal habitats.

c. Climate Regulation

Restored ecosystems can function as carbon sinks, effectively soaking up and holding onto carbon dioxide from the air. This process aids in reducing the impacts of climate change. Sustainable restoration efforts play a role in decreasing greenhouse gas emissions and alleviating climate change by fostering plant growth and enhancing soil health. As a result, this contributes to the regulation of worldwide temperatures and the reduction of climate change effects (Lal, 2012).

B. Economic Viability

a. Resource Recovery

Sustainable reclamation makes recovering metals and other valuable elements from mining waste possible. This method helps create a circular economy that recycles and reuses resources, which in turn decreases the need for more mining operations. In addition to reducing the negative effects on the environment, resource recovery has the potential to bring about significant economic benefits from mining (Moreira et al., 2021).

b. Long-term Cost Savings

Sustainable reclamation techniques have the potential to save a lot of money in the long run. Future health implications and cleaning costs may be mitigated via early and effective environmental issue management. By taking this precautionary measure, the likelihood of having to pay for expensive clean-up efforts and avoid any legal liabilities may decrease (Karn et al., 2009).

c. Sustainable Land Use

Agricultural, forestry, or recreational uses are just a few of the many potential benefits of reclaimed land. This sustainable land-use technique results in consistent financial benefits and the maintenance of local economies. Converting unusable or contaminated land into productive areas can provide long-term economic assets to communities and raise living standards generally (Keenan & Holcombe, 2021).

C. Social Responsibility

a. Community Health

Reducing healthcare costs and improving public health are two major outcomes of using sustainable reclamation strategies to reduce environmental hazards. Communities may be able to drastically cut down on health problems caused by pollution in the environment if they undertake cleanup and take steps to limit their exposure to harmful substances. Better overall health and lower healthcare expenses are the results of this (Hanjra et al., 2012).

b. Job Creation

Reclamation programs provide employment opportunities, especially in rural and disadvantaged areas. These projects often require a diverse workforce consisting of engineers, scientists, laborers, and support staff. Sustainable rehabilitation plays a vital role in fostering economic development and alleviating poverty in areas affected by providing job opportunities (Adjei, 2010).

c. Enhanced Quality of Life

The creation of eco-friendly zones and the improvement of land use via sustainable reclamation efforts contribute to the betterment of living conditions and the general welfare of local populations. Green areas provide recreational possibilities, improve air quality, and support mental and physical health. By transforming formerly accessible and unproductive land into usable and beneficial areas, communities may achieve an improved quality of life (Jin et al., 2021).

D. Legal and Regulatory Compliance

a. Meeting Regulations

Many countries have strong regulations regarding land reclamation and environmental protection. By implementing sustainable practices, organizations ensure compliance with these criteria, thus avoiding legal penalties and potential lawsuits. Companies and organizations demonstrate their commitment to responsible management of the environment by adhering to regulatory requirements (Peterson, 2013).

b. Corporate Responsibility

Companies engaged with environmentally friendly reclamation practices demonstrate a dedication to both social and environmental accountability, thus enhancing their reputation and gaining the trust of stakeholders. By prioritizing sustainable practices, firms may cultivate positive relationships with local communities, governments, and investors. Adopting corporate responsibility may lead to more support and improved business opportunities (Hall & Jeanneret, 2015).

E. Long-term Sustainability

a. Resilience to Environmental Changes

Using sustainable reclamation strategies, we may create landscapes that possess the capacity to withstand and adjust to variations in the environment, such as climate change. By enhancing the health and stability of ecosystems, these approaches provide long-term environmental stability and reduce vulnerability to climate-related impacts. Resilience and the capacity to recover are crucial for maintaining the benefits of reclamation efforts throughout time (El et al., 2020).

b. Sustainable Development Goals

To help achieve sustainability on a global scale, it is important to align reclamation practices with the United Nations Sustainable Development Goals (SDGs). Environmentally responsible reclamation practices may advance numerous Sustainable Development Goals (SDGs). This is especially true in the areas of water purification, biodiversity preservation, and climate change mitigation. Stakeholders may help create a better, more equitable future by including these goals in reclamation efforts (Obaideen et al., 2022).

Tailings

For many decades, the mining sector has been a key driver of economic expansion and has continued to develop (Figure 2). The presence of large copper deposits in the Copperbelt and Northwestern regions is the main cause of this. Trace amounts and deposits of a wide variety of minerals can be found all around the country. The main mining regions, which are home to many copper mines, are the Copperbelt and Northwestern Provinces (Sikamo et al., 2015). The process of extracting precious minerals from mine leaves behind tailings, which are the remnants of finely crushed rock. Additionally, they consist of mineral processing chemicals and process water, the latter of which includes dissolved metals (Edraki et al., 2014).

Tailings consist of significant amounts of heavy metals and hazardous substances that spread across extensive areas of land. The substances mentioned are compounds containing sulfur and metallic elements like Copper, Iron, Manganese, Cobalt, Zinc, and others. These compounds are often held in embankments (Ngulube et al., 2016). The environmental impacts of mining tailings ponds are significant and need substantial measures to make the area ecologically sustainable. “Tailings deposits frequently pose the greatest environmental risks in mining development projects” (Baghdasaryan, 2016). Owing to their lack of economic value to the mine operator, tailings are usually kept in the most cost-efficient way that satisfies the minimal regulatory requirements. It is crucial to consider the hazards linked with the latter. This study is dedicated to examining the environmental impacts of tailing dams in the following areas:

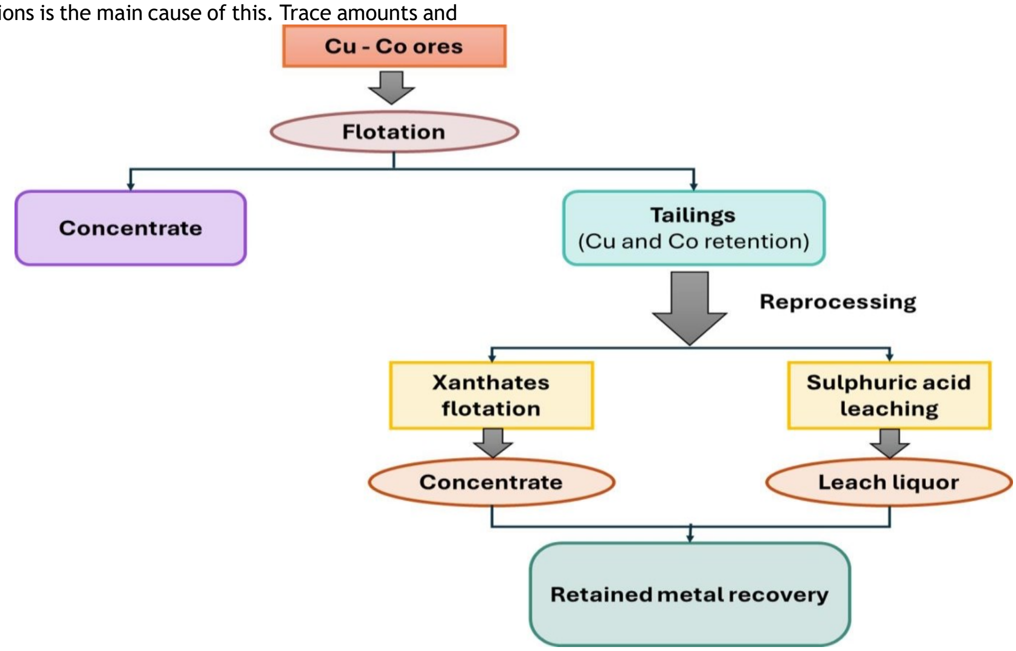

Figure -2: Flowchart for the Extraction and Recovery of Cu and Co from Ores.

Water contamination occurs because of the discharge of solid waste, heavy metals, and other chemical compounds from tailings overflows. If a dam is constructed without proper technical considerations, there is a significant likelihood that excessive rainfall might result in the dam bursting or being eroded. This could lead to flooding in nearby water bodies and neighboring farmlands. The leachate from wet aquifers into subsurface aquifers, causing contamination (Adamo et al., 2020).

The atmosphere is contaminated by particulate matter originating from the landfill (Kossoff et al., 2014).

The dumpsite causes the land it occupies to permanently lose its fertility, making it unsuitable for agriculture or as a home for animals. It also prevents the land from being used for grazing livestock. In 1980, in Tyrone, Mexico, there was a breach in a dam wall caused by a sudden and significant rise in its height, resulting in the build-up of excessive pressure inside the dam. Therefore, there is a discharge of tailings that travel 8 kilometers downstream and flood agricultural areas (Adamo et al., 2020).

Soil pollution and disruptions occur when sulfides encounter water and are oxidized, resulting in the formation of ecologically harmful acid mine drainage (Norgate & Rankin, 2000). During this process, the leaching of metal is intensified in tailings (2019).

The biodiversity is being destroyed because of the harsh circumstances on the dumpsite.

In 1996, the tailing dam collapse in Mar Copper, Philippines, resulted in the evacuation of people, loss of life, and suspension of commercial activities. This occurrence necessitates the consideration of unforeseen expenses related to environmental damage and the expenditures associated with cleaning up (Adamo et al., 2020).

The environmental impacts have both direct and indirect consequences for the social component of the region and downstream areas. The local populace responds to the pollutants emitted by the tailings. These factors may result in the forced removal of people from their homes and have a significant effect on their ability to earn a living. The conclusion should include recommendations for the use of established techniques to restore ecological equilibrium or efficiently handle risks and failures.

ENVIRONMENTAL IMPACT OF COPPER TAILINGS DAMS

Copper tailings dams play a vital role in mining operations by providing storage facilities for the large amounts of waste produced during the extraction and processing of ores. Nevertheless, these constructions are accompanied by substantial environmental and safety considerations (Table-1).

Table- 1: Environmental Impact of Copper Tailings [25,26,3,27].

Impact Area	Description	Case Studies
Soil and Water Contamination	Heavy metals and hazardous substances from tailings seep into soil and groundwater, causing contamination.	Contamination of soil and water in Zambia's Copperbelt Province.
Ecosystem Disruption	Fine particulate matter and toxic chemicals from tailings disrupt plant and animal life, reducing biodiversity.	Disruption of aquatic ecosystems in Chile due to tailings deposition.
Human Health Risks	Exposure to toxic chemicals from tailings can cause respiratory problems, cancer, and neurological disorders in nearby communities.	Health issues in communities near tailings dams in Peru.
Tailings Dam Failures	Structural failures of tailings dams can release massive amounts of toxic waste, causing immediate and long-term environmental damage.	Brumadinho dam disaster in Brazil, 2019.

Soil and Water Contamination

Copper tailings include a diverse range of dense metals and dangerous substances, such as arsenic, lead, and cadmium. These contaminants can infiltrate the adjacent soil and groundwater, leading to significant pollution. Insufficient containment of tailings may result in the infiltration of harmful substances into aquifers, leading to adverse impacts on both the environment and human health. Water source contamination may have adverse impacts on farming, drinking water supplies, and aquatic environments, resulting in long-term damage to the environment (Edraki et al., 2014).

Ecosystem Disruption

The disposal of tailings results in substantial disruption to adjacent ecosystems. Tailings consist of tiny particles that may asphyxiate plants, resulting in a reduction in plant diversity and alterations to ecosystems. The presence of hazardous substances in tailings may potentially endanger animals, leading to a decrease in biodiversity. Aquatic ecosystems are very vulnerable to harm since dirty water discharged from tailings dams may lead to the accumulation of hazardous metals in fish and other aquatic animals. This presents a substantial threat to the whole food web (Rilwanu, 2021).

Human Health Risks

The proximity of tailings dams to neighboring villages is a potential hazard since these populations are at risk of being exposed to hazardous substances. Breathing dust particles from dried tailings might result in lung difficulties and several other health conditions. The consumption or use of water that is polluted may lead to the onset of chronic illnesses, such as cancer and neurological disorders. It is crucial to prioritize the secure management and appropriate disposal of tailings to protect public health (Burritt and Christ, 2018).

Tailings Dam Failures

The collapse of tailings dams is a very catastrophic danger. These failures possess the capacity to release millions of metric tons of dangerous waste into the environment, causing rapid and substantial damage. The Brumadinho dam incident in Brazil in 2019 resulted in loss of life, significant environmental destruction, and long-lasting ecological and socioeconomic impacts. The substantial potential energy stored in these dams suggests that any rupture may lead to catastrophic consequences, highlighting the need for stringent safety measures and monitoring (Adeola, 2012).

Climate Change and Weather Events

Climate change exacerbates the issues associated with tailings dams. Climate events occurring more frequently and intensely, like flooding and heavy downpours, can overwhelm these structures and cause breaches. To address these problems and ensure the long-term stability of tailings dams, it is crucial to use rigorous design and maintenance methods, as well as adopt adaptive management solutions (Mudd and Boger, 2013).

MITIGATION AND MANAGEMENT STRATEGIES

To mitigate the environmental impact of copper tailings dams, it is necessary to employ a variety of crucial strategies. Improved engineering and design may considerably enhance the stability and safety of these structures. Utilizing technological developments such as the use of paste and thicker tailings, enhanced dam materials, and efficient water management has the potential to reduce the probability of failures (Meggyes & Debreczeni, 2006). Regularly monitoring and maintaining infrastructure is of utmost importance. This may be achieved by applying sophisticated technologies like remote sensing and geotechnical sensors. These technologies help in swiftly identifying and resolving any issues that may arise (Soga et al., 2019). Environmental restoration, including practices like re-vegetation and pollution mitigation methods, is essential for restoring ecological balance and minimizing long-term impacts (Oraon et al, 2023). Adhering strictly to environmental regulations and standards ensures the use of safer practices in managing tailings, which holds mining businesses accountable and protects public health (Poswa & Davies, 2017).

REMEDIATION METHODS FOR COPPER TAILINGS DAMS

Due to the possible discharge of hazardous elements into the nearby ecosystem, tailings of the leftover materials left over after precious minerals are extracted pose serious threats to human health and the environment. Efficient management of these tailings necessitates a holistic strategy that integrates physical, chemical, and biological remediation techniques, along with integrated tactics that augment the overall efficacy of these procedures. This paper presents a comprehensive examination of the several techniques used to control and minimize the ecological consequences of tailings. It specifically concentrates on their practical uses, benefits, and constraints (Edraki et al., 2014).

A. Physical Remediation

a. Containment and Capping

Containment and capping are crucial physical cleanup methods intended to separate tailings from the surrounding ecosystem, thus reducing the dissemination of pollutants. Containment entails the construction of barriers, such as constructed berms or synthetic liners, around tailings storage facilities to limit the passage of contaminants. Capping is the process of placing layers of inactive materials such as clean soil, clay, or synthetic membranes atop tailings. These layers may be further vegetated to stabilize the surface and prevent erosion. These approaches are very efficient in mitigating the danger of water penetration, decreasing the creation of dust, and preventing direct contact with pollutants. As a result, they significantly reduce the possibility of environmental contamination and human exposure (Padhye et al., 2023).

b. Solidification/Stabilization

Solidification and stabilization are methods used to decrease the movement of pollutants inside tailings by modifying their characteristics via chemical or physical means. Solidification involves the incorporation of binding chemicals, such as cement or lime that envelop the tailings and convert them into a denser and more stable state. Stabilization refers to the process of chemically modifying pollutants in the tailings to transform them into less dangerous substances. This reduces their ability to dissolve and the risk of their leaking into the environment. These approaches improve the structural strength of tailings, making them more secure for long-term storage or possible use in buildings and other purposes (Luo et al., 2022).

B. Chemical Remediation

a. Chemical Leaching

Chemical leaching is a remediation technique that employs chemical solutions to extract pollutants from tailings with specificity. This procedure entails the use of acidic, alkaline, or complex chemicals to dissolve certain harmful compounds, such as heavy metals, therefore facilitating their extraction from the tailing's material. The efficacy of chemical leaching is contingent upon the characteristics of the pollutants and the attributes of the tailings. It is often used with other remediation techniques to achieve thorough treatment and reduce the environmental consequences of tailings (Nguyen et al., 2021).

b. Soil Washing

Soil washing is a remediation method that employs a physical-chemical process to remove pollutants from tailings using water or chemical solutions. This method is very efficient in eliminating pollutants that are bonded to particles, and it may be further improved by adding surfactants or other chemical substances to increase the solubility of contaminants. Soil washing may be performed either in the location where it is needed or at a different location, and the purified waste materials can often be reused or disposed of safely. This approach has the benefit of quickly decreasing pollutant levels, but it requires meticulous handling of the ensuing effluent and byproducts (Liu et al., 2021).

C. Biological Remediation

a. Phytoremediation

Phytoremediation is a sustainable method of remediation that uses plants to absorb, collect, and detoxify pollutants from tailings. Some plant species can absorb heavy metals and other harmful elements via their roots, storing them in their biomass. Phytoremediation gradually decreases the level of pollutants in the tailings while simultaneously stabilizing the soil and minimizing erosion. The efficacy of phytoremediation relies on the careful selection of appropriate plant species, such as *Brassica juncea* (Indian mustard) or *Populus* spp. (poplars), as well as the specific environmental circumstances of the location (Nedjimi, 2021).

b. Bioremediation

Bioremediation uses microorganisms to break down, convert, or take off harmful substances present in tailings. Microbial activities, such as bioleaching and biotransformation, may be used to degrade organic contaminants or immobilize heavy metals, thereby decreasing their environmental consequences. Biostimulation, which involves the introduction of nutrients or other chemicals to stimulate microbial activity, might further increase the effectiveness of bioremediation. This approach is both economical and environmentally friendly, but it needs meticulous supervision and fine-tuning to guarantee the attainment of the intended results (Padhan et al., 2021).

C. Integrated Approaches in Tailings Remediation

In India, like other areas, comprehensive remediation strategies are often used to tackle the complex issues associated with tailings management. Typically, these procedures start with physical containment measures, such as capping and stability, to reduce immediate dangers. Subsequently, chemical processes like leaching and stabilization are used to target and mitigate certain pollutants. Ultimately, the use of biological techniques such as phytoremediation and bioremediation are employed to restore the impacted ecosystems. By combining these techniques, a more thorough and enduring approach to tailings management is accomplished, effectively addressing immediate risks and promoting long-term ecological recovery.

CASE STUDIES OF SUCCESSFUL REMEDIATION PROJECTS IN INDIA

Case study 1

The Malanjkhand Copper Project is among India's most extensive open-pit copper mines. The management of tailings at this location has used a mix of physical confinement and chemical stabilizing methods. Utilizing readily accessible materials for covering and employing phytoremediation with indigenous plant species have been crucial tactics in mitigating the ecological consequences of tailings. These efforts have not only achieved the stabilization of the tailings but also facilitated the restoration of indigenous plant life, enhancing the overall ecological equilibrium (Soni, 2019).

Case study 2

The management of tailings at the Jaduguda Uranium Mines has been a major problem because of the radioactive properties of the material. The remediation approach used in this case involves the integration of physical confinement using constructed barriers, chemical stabilization using lime and other neutralizing agents, and biological techniques, such as the utilization of hyperaccumulator plants for phytoremediation. The execution of this comprehensive plan has played a vital role in managing the dissemination of pollutants and rejuvenating the nearby ecosystem (Jha et al., 2019).

Case study 3

The Zawar Mines, renowned for their lead-zinc output, have successfully developed an extensive program to manage the disposal of waste materials known as tailings. This encompasses the construction of tailings dams equipped with physical barriers, the utilization of chemical processes to counteract the acidity of tailings, and the implementation of phytoremediation methods using indigenous grasses and shrubs. The efficacy of this comprehensive strategy is seen in the decrease of leachate pollution and the progressive restoration of indigenous biodiversity (Kumar & Golani, 2023).

THE PRESENT STATUS OF COPPER MINING AND TAILINGS MANAGEMENT

The copper mining business continues to be crucial, fueled by the need for copper in diverse sectors such as electrical wire, electronics, and renewable energy technology (Igogo et al., 2021). Nevertheless, the sector has substantial obstacles, namely in the realm of tailings management.

The global copper mining industry is distinguished by the exploitation of substantial deposits, mostly situated in regions such as Chile, Peru, and the United States. The production process involves the extraction of ore, subsequent crushing, and additional processing to separate copper from waste rock. As a result of the decline in ore quality, a greater quantity of ore must be processed to extract the same amount of copper. As a result, there is an increased quantity of tailings generated (Falagan et al., 2017).

Tailings, the leftover material that remains after the extraction of valuable minerals, pose a substantial environmental challenge. Tailings, which are the byproduct of ore processing, may account for a substantial amount, ranging from 95% to 99% of the overall processed ore. This waste often contains perilous substances, such as toxic metals and chemicals used in the extraction of minerals from ores (Kalisz et al., 2022). It is essential to prioritize the secure and sustainable handling of these tailings to minimize any adverse impacts on the environment.

CHALLENGES IN TAILINGS MANAGEMENT

The primary challenges in tailings management include:

Environmental Risks

Tailings have the potential to pollute land and water, negatively impact biodiversity, and provide health hazards to nearby populations. Tailings dam failures may result in severe environmental catastrophes (Santamarina et al., 2019).

Technical and Engineering Issues

Ensuring the structural integrity of tailings dams is a multifaceted task. Technological advancements in the field of engineering can reduce some risks, however, unforeseen failures may still happen (Clarkson, & Williams, 2021).

Regulatory Compliance

Ensuring compliance with environmental standards is crucial but may pose difficulties, particularly in areas with less robust regulatory frameworks (Weiss & Jacobson, 2000).

Economic Constraints

Owing to the significant expenses involved, smaller mining companies may have difficulties in deploying modern tailings management technologies (Hilson, 2000).

IMPORTANCE OF ADDRESSING TAILINGS MANAGEMENT

Addressing the management of tailings is essential for achieving sustainable development. Efficient management of tailings may safeguard the environment by minimizing the pollution of ecosystems and water supplies, conserving biodiversity, and reducing the likelihood of environmental catastrophes. By enhancing the stability of tailings dams, it has the potential to improve safety and avoid catastrophic collapses. Furthermore, it fosters social accountability by guaranteeing that mining activities do not have adverse effects on nearby populations, thereby enhancing health and living standards. Furthermore, the implementation of efficient tailings management guarantees adherence to regulatory requirements, assisting mining businesses in achieving environmental benchmarks and preventing legal repercussions (Array et al., 2021).

FUTURE DIRECTIONS

Looking ahead, the future of tailings management will likely be shaped by advancements in technology and a greater emphasis on sustainability. Innovations such as advanced materials for tailings encapsulation, more efficient chemical treatment methods, and enhanced phytoremediation techniques offer promising avenues for improving reclamation efforts. Additionally, the integration of digital tools like remote sensing and data analytics can provide real-time monitoring and better management of tailings facilities. Collaborative research and development, alongside stronger regulatory frameworks and community engagement, will be essential in addressing the complex challenges of tailings management. Emphasizing a circular economy approach, where tailings are treated as resources rather than waste, will also play a pivotal role in advancing sustainable mining practices.

CONCLUSION

Effective management of mine tailings is crucial for minimizing environmental and health impacts associated with mining operations. This review underscores the importance of sustainable reclamation techniques, encompass biodiversity preservation, pollution control, climate regulation, and resource recovery. Current practices, including physical, chemical, and biological remediation, have demonstrated varying degrees of success in mitigating the adverse effects of tailings. Case studies, particularly those from regions with high tailings output, like India, highlight both the progress made and the ongoing challenges in tailings management. The necessity for robust, integrated approaches to tailings reclamation is clear, aiming to balance ecological health, economic viability, and regulatory compliance.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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