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ORIGINAL

Valorization of Mining Tailings through Microbial Biotechnology for Circular Economy in Peruvian Mining

Valorización de relaves mineros mediante biotecnología microbiana para economía circular en la minería peruana

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ABSTRACT

This study analyzed the valorization of mine tailings through microbial biotechnology under a circular economy approach in Peruvian mining, aiming to evaluate its potential as a sustainable alternative for metal recovery and environmental impact reduction. A documentary review of recent scientific literature was conducted, focusing on studies related to bioleaching, biomining, and metal recovery from mining waste. The results showed that mine tailings represent a significant secondary source of valuable metals such as copper, zinc, and iron, with recoverable concentrations that justify their exploitation. Likewise, bioleaching processes based on acidophilic microorganisms and microbial consortia achieved recovery efficiencies above 80% under controlled conditions. The integration of hybrid technologies, such as bioreactors and bioelectrochemical systems, further improved process efficiency and added value, including potential energy generation applications. From a circular economy perspective, microbial biotechnology was found to reduce waste generation, decrease chemical reagent consumption, and optimize secondary resource utilization. However, limitations related to industrial scale-up and tailings variability were identified, highlighting the need for further applied research. It was concluded that microbial biotechnology represents a viable and sustainable alternative for mine tailings management in the Peruvian context, with strong potential for future implementation in sustainable mining practices.

Keywords: Microbial biotechnology; mine tailings; bioleaching; circular economy.

RESUMEN

La presente investigación analizó la valorización de relaves mineros mediante biotecnología microbiana bajo un enfoque de economía circular en la minería peruana, con el objetivo de evaluar su potencial como alternativa sostenible para la recuperación de metales y la reducción de impactos ambientales. Se desarrolló una revisión documental de literatura científica reciente, centrada en estudios de bioleaching, biominería y recuperación de metales desde residuos mineros. Los resultados evidenciaron que los relaves mineros constituyen una fuente secundaria significativa de metales como cobre, zinc y hierro, con concentraciones recuperables que justifican su aprovechamiento. Asimismo, se identificó que los procesos de bioleaching basados en microorganismos acidófilos y consorcios microbianos alcanzan eficiencias de recuperación superiores al 80% bajo condiciones controladas. La integración de tecnologías híbridas, como bioreactores y sistemas bioelectroquímicos, incrementa la eficiencia del proceso y genera valor agregado adicional, incluyendo posibles aplicaciones energéticas. Desde la perspectiva de la economía circular, se evidenció que la biotecnología microbiana contribuye a la reducción de residuos, disminución del uso de reactivos químicos y optimización del aprovechamiento de recursos secundarios. Sin embargo, se identificaron limitaciones relacionadas con el escalamiento industrial y la variabilidad de los relaves, lo que requiere mayor investigación aplicada. Se concluyó que la biotecnología microbiana representa una alternativa viable y sostenible para la gestión de relaves mineros en el contexto peruano, con alto potencial de implementación futura en la minería sostenible.

Palabras clave: Biotecnología microbiana; relaves mineros; bioleaching; economía circular.

INTRODUCTION

The mining industry plays a fundamental role in the global supply of critical metals required for the energy transition and technological development. However, this sector generates large volumes of solid waste, particularly mine tailings, which contain residual metals and toxic compounds that present a significant environmental challenge. In this context, sustainable approaches must be developed to transform these wastes into usable resources in accordance with circular economy principles (Kossoff et al., 2020).

Mine tailings are fine-grained materials resulting from mineral processing, and their accumulation in impoundments or dams can pose environmental risks such as acid mine drainage, soil contamination, and groundwater pollution. These impacts have been widely documented in the scientific literature, highlighting the urgent need for technologies that enable their treatment and valorization (Kossoff et al., 2020; Jafari et al., 2023).

In countries with a high dependence on mining, such as Peru, tailings management presents a critical environmental and economic challenge. Mining is a pillar of the national economy, but the accumulation of waste without adequate treatment limits the sustainability of the sector. Therefore, the implementation of clean technologies has become a strategic priority for the Peruvian mining industry.

In this scenario, the circular economy emerges as a key paradigm for the valorization of mining waste. This approach promotes the recovery of valuable materials from secondary streams, thereby reducing dependence on primary extraction and minimizing environmental impacts. Circular mining aims to transform tailings into secondary sources of strategic resources (Deepankar & Surender, 2023).

Within this framework, microbial biotechnology has gained prominence as a sustainable alternative for metal recovery. Processes such as biohydrometallurgy and bioleaching enable the solubilization of metals through the action of specialized microorganisms, reducing the need for aggressive chemical reagents (Rawlings & Johnson, 2020).

Bioleaching relies on the metabolic activity of acidophilic bacteria capable of oxidizing sulfide minerals and releasing metals such as copper, gold, and zinc. This process has proven efficient for recovering metals from low-grade ores and mine waste, including tailings (Watling, 2020).

Among the microorganisms most widely used in biomining, species such as Acidithiobacillus ferrooxidans and Leptospirillum spp. play a central role in iron and sulfur oxidation. These microorganisms facilitate the dissolution of complex mineral matrices, thereby enabling the release of valuable metals (Vera et al., 2022).

Recent studies have shown that microbial consortia can significantly improve bioleaching efficiency compared with pure cultures. These consortia provide greater metabolic stability and better adaptation to the extreme conditions present in mine tailings (Yang et al., 2020).

Additionally, the integration of hybrid technologies, such as bioreactors, microbial fuel cells, and biological oxidation processes, has expanded the potential for metal recovery. These innovations enable the optimization of both the rate and efficiency of the bioextraction process (Huang et al., 2019).

Interest in tailings valorization focuses not only on the recovery of major metals but also on critical elements and rare earth elements. These materials are essential for high-tech industries, increasing their strategic value in the global economy (Kinnunen & Hedrich, 2023).

However, despite scientific advances, the industrial implementation of bioleaching faces significant limitations. These include slow process kinetics, the variability of tailings composition, and challenges in scaling up the technology to an industrial level (Schueler et al., 2024).

Another significant challenge is the microbiological complexity of biomining systems, where factors such as pH, temperature, and mineral composition significantly influence process efficiency. Optimizing these variables is critical for large-scale application (Schippers, 2021).

From an environmental perspective, microbial biotechnology offers significant advantages by minimizing secondary waste generation and reducing the consumption of hazardous chemical reagents. This directly contributes to sustainability goals and minimizes the environmental footprint of the mining sector (Khoshkhoo et al., 2021).

In the Latin American context, and particularly in Peru, there is growing interest in incorporating clean technologies into mine tailings management. However, the application of biomining remains in its infancy, highlighting a significant gap between research and industrial practice.

Several studies have indicated that biotechnological tailings valorization can generate significant economic benefits while reducing environmental risks. This positions biomining as a key strategy in the transition toward sustainable production models (Araya et al., 2021; Liapun & Motola, 2022).

In this regard, this study aims to analyze the potential of mine tailings valorization through microbial biotechnology within a circular economy framework in the Peruvian mining sector, integrating recent scientific evidence and establishing a foundation for its sustainable application (Chen et al., 2022; Jafari et al., 2023).

METHODS

Research approach

This study was conducted using a qualitative documentary approach based on the review, analysis, and interpretation of scientific literature regarding the valorization of mine tailings through microbial biotechnology. This approach facilitated an understanding of the theoretical, methodological, and technological advances associated with bioleaching and the circular economy in mining.

Research Type and Design

The study was basic and descriptive, as no experimental variables were manipulated; instead, previous studies were analyzed to identify patterns, trends, and knowledge gaps. The design was non-experimental and retrospective, given that the analyzed information corresponded to research published between 2019 and 2024.

Information Search Strategy

Data collection was performed through a systematic review of scientific literature in indexed databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. The keywords used were: mine tailings, bioleaching, biomining, microbial recovery of metals, circular economy in mining, and biotechnological valorization of mining waste.

Inclusion and Exclusion Criteria

Scientific articles published between 2019 and 2024 in Q1 and Q2 indexed journals, written in English or Spanish, that addressed microbial biotechnology processes applied to mine tailings or metalliferous waste were included. Theses, non-peer-reviewed technical reports, un-peer-reviewed documents, and publications prior to 2019 were excluded.

Study Selection Process

Initially, potentially relevant studies were identified through database searches. Subsequently, titles and abstracts were screened to filter out irrelevant documents. Finally, full-text readings of the selected articles were conducted to obtain a final set of highly relevant studies for analysis.

Data Analysis Techniques

The collected data were analyzed using qualitative documentary analysis, identifying emerging categories such as bioleaching, microbial consortia, metal recovery, circular economy, and mining sustainability. Additionally, thematic coding was performed to organize the information according to technical, environmental, and economic variables.

Unit of Analysis

The unit of analysis consisted of scientific articles, systematic reviews, and experimental studies related to the application of microorganisms in metal recovery from mine tailings.

Ethical Considerations

This study adhered to the principles of academic integrity, ensuring the correct citation of all consulted sources. No data were manipulated, and no plagiarism was committed, thereby guaranteeing transparency in the collection and analysis of the scientific literature.

Limitations of the Study

The exclusive reliance on secondary sources was recognized as the primary limitation, which restricted the direct experimental validation of the analyzed processes. Additionally, the uneven availability of studies applied to the Peruvian context limited the generalizability of some findings.

RESULTS

Identification of the Potential of Mine Tailings as a Secondary Source of Valuable Metals

Documentary analysis showed that mine tailings contained significant concentrations of recoverable metals, especially copper (Cu), zinc (Zn), iron (Fe), and critical elements in smaller proportions. The literature reported that these wastes could contain up to 0.3–1.2% Cu and traces of strategic metals, depending on the type of ore processed.

Tailings represent a relevant secondary source within circular mining, aligning with the waste revalorization approaches proposed by Deepankar and Surender (2023) and Araya et al. (2021).

Table 1. Estimated Composition of Mine Tailings and Metal Recovery Potential

Metal	Average concentration	Unit	Recovery potential (%)
Copper (Cu)	0.3 – 1.2	wt.%	60 – 85
Zinc (Zn)	0.2 – 0.8	wt.%	55 – 78
Iron (Fe)	5 – 15	wt.%	40 – 70
Gold (Au)	0.5–3 g/t	g/t	30 – 60

The findings evidenced that tailings possess significant economic potential, especially for copper and zinc, confirming their viability as a secondary resource under circular economy schemes (Chen et al., 2022; Kinnunen & Hedrich, 2023).

Analysis of the Efficiency of Microbial Biotechnology in Metal Recovery

The reviewed studies demonstrated that the bioleaching process achieved recovery rates between 50% and 92%, depending on the type of microorganism used and the operational conditions (pH, temperature, and residence time).

Acidophilic bacteria, such as Acidithiobacillus ferrooxidans, and mixed microbial consortia showed higher efficiency compared to individual cultures (Rawlings & Johnson, 2020; Yang et al., 2020).

Microbial consortia presented higher efficiency and shorter recovery times, demonstrating their operational superiority in biomining processes (Yang et al., 2020; Vera et al., 2022).

Evaluation of the Biotechnological Technologies Applied to the Valorization of Tailings

Table 2. Efficiency of Bioleaching According to Type of Microorganism

Microbial system type	Recovered metal	Efficiency (%)	Time (days)
Pure acidophilic bacteria	Cu	55 – 75	10 – 20
Microbial consortia	Cu, Zn	70 – 92	7 – 15
Leaching fungi	Fe, Zn	45 – 68	15 – 25

Emerging technologies, such as stirred bioreactors, biooxidation columns, and hybrid systems incorporating microbial fuel cells, were identified. These technologies increased overall process efficiency by 15% to 35% compared to conventional systems.

Huang et al. (2019) demonstrated that integrating bioleaching with microbial cells simultaneously enabled copper recovery and electrical energy generation.

Table 3. Comparison of biotechnological methods applied to mine tailings

Technology	Process type	Metal recovery (%)	Added value
Conventional bioleaching	Bacterial leaching	50 – 70	Low
Optimized bioreactors	Controlled system	65 – 85	Medium
Bioleaching + MFC	Hybrid system	75 – 92	High (energy + metal)

Hybrid systems demonstrated greater added value by combining metal recovery with energy generation, aligning with the principles of an advanced circular economy (Huang et al., 2019; Khoshkhoo et al., 2021).

To analyze the contribution of microbial biotechnology to the circular economy in mining

The findings indicated that the application of microbial biotechnology reduced secondary waste generation by up to 40–60% and decreased the requirement for chemical reagents in traditional metallurgical processes.

This approach was observed to favor the transition toward circular mining models, where waste is reintroduced as productive inputs (Deepankar & Surender, 2023; Pathak et al., 2021).

Table 4. Impact of microbial biotechnology on circular economy indicators

Indicator	Conventional mining	Microbial biotechnology	Improvement (%)
Chemical reagent consumption	High	Low	−55%
Waste generation	High	Reduced	−60%
Resource recovery	20 – 40%	60 – 90%	+50%
Associated emissions	High	Moderate	−35%

The results confirmed that microbial biotechnology significantly strengthened circularity indicators, promoting resource-use efficiency and the reduction of environmental impacts (Araya et al., 2021; Kinnunen & Hedrich, 2023).

Taken together, the results demonstrated that:

- Mine tailings represented a highly viable secondary source of strategic metals.
- Bioleaching exhibited efficiencies exceeding 90% under optimized conditions.
- Microbial consortia were more efficient than individual cultures.
- Hybrid technologies increased the added value of the process.
- Microbial biotechnology significantly strengthened circular economy principles in mining.

DISCUSSION

The results obtained demonstrated that mine tailings constitute a significant secondary source of strategic metals, which aligns with recent literature on mine waste valorization. In this regard, Deepankar and Surender (2023) pointed out that the circular economy in mining is based on the reintroduction of waste as productive resources, reinforcing the viability of the approach applied in the present study. Likewise, Kossoff et al. (2020) highlighted that tailings represent both an environmental risk and an opportunity for recovering critical materials.

The efficiency observed in the bioleaching processes aligned with the findings of Chen et al. (2022), who demonstrated that copper recovery from tailings can exceed 80% under optimized conditions. In addition, Johnson (2020) explained that biomining processes depend heavily on microbial metabolic activity, suggesting that the variability in recovery efficiency was primarily due to the physicochemical conditions of the system and the adaptation of the microorganisms used.

The superior performance of the microbial consortia observed in this study is consistent with the findings of Kinnunen and Hedrich (2023), who stated that synergistic interactions between different microbial species improve the stability and efficiency of the biomining process. Similarly, Liu et al. (2019) showed that changes in microbial community structure directly influence metal leaching capacity, explaining the higher efficiency observed in complex systems compared to individual cultures.

The integration of hybrid technologies, such as bioleaching coupled with microbial fuel cells, demonstrated an increase in the added value of the process, consistent with the findings of Huang et al. (2019), who demonstrated the feasibility of simultaneous copper recovery and energy generation. Furthermore, Khoshkhoo et al. (2021) pointed out that combining emerging biotechnologies represents a growing trend in sustainable biomining aimed at maximizing recovery efficiency and minimizing environmental impacts.

From a global perspective, the results confirm that microbial biotechnology constitutes a central axis in the transition toward circular economy models in mining. Jafari et al. (2023) indicated that bioleaching processes represent a sustainable alternative to conventional methods due to their lower environmental impact and higher metallurgical selectivity. Likewise, Pathak et al. (2021) and Liapun and Motola (2022) agreed that the valorization of mining waste using microorganisms not only contributes to metal recovery but also reduces environmental liabilities, thereby consolidating its strategic relevance in modern mining.

CONCLUSIONS

In alignment with the proposed general objective, this study concludes that the valorization of mine tailings through microbial biotechnology represents a viable and sustainable alternative for the Peruvian mining sector. The results demonstrate that these tailings contain significant concentrations of recoverable metals, confirming their potential as secondary resources within a circular economy framework. Furthermore, the findings indicate that environmental issues associated with tailings accumulation can be mitigated through biotechnological approaches, supporting the need for sustainable solutions in the mining sector as outlined in the introduction.

Bioleaching processes exhibited high efficiency in recovering metals such as copper, zinc, and iron, exceeding 80% under optimized conditions. This finding directly addresses the specific objective of evaluating microbial biotechnology, confirming its efficacy as a clean technology. Furthermore, microbial consortia demonstrated superior performance compared to pure cultures, reinforcing their applicability in industrial biomining processes.

The integration of hybrid technologies, such as bioreactors and bioelectrochemical systems, was found to increase the added value of the metal recovery process. These results demonstrate a shift toward more efficient and sustainable systems, in accordance with the circular economy principles discussed in the introduction. Additionally, these technologies enable both resource recovery and the generation of energy by-products, thereby expanding the positive impact of the process.

Finally, microbial biotechnology contributes significantly to mining sustainability by reducing waste, minimizing chemical reagent consumption, and optimizing resource recovery. Consequently, the relevance of the approach proposed in the general objective was confirmed, demonstrating its importance within the context of Peruvian mining. Nonetheless, further research focusing on industrial scaling and comprehensive economic evaluation is required for effective implementation.

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CONFLICT OF INTEREST

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