
Exploration of Stakeholder Perceptions on the Application of Biomining for Mining Waste Management

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Diinput : 12 August 2025

Diterima : 21 August 2025

Direvisi : 28 August 2025

Diterbitkan : 28 August 2025

ABSTRAK

Pengelolaan limbah tambang merupakan tantangan besar yang berdampak pada pencemaran air, degradasi ekosistem, dan akumulasi logam berat. Biomining, yakni pemanfaatan mikroorganisme untuk mengekstraksi dan menstabilisasi logam, dipandang sebagai solusi inovatif yang lebih ramah lingkungan dibanding metode konvensional. Penelitian ini bertujuan mengeksplorasi persepsi pemangku kepentingan regulator, perusahaan tambang, masyarakat lokal, dan akademisi terhadap penerapan biomining dalam pengelolaan limbah tambang. Penelitian menggunakan pendekatan kualitatif deskriptif dengan desain studi kasus. Data diperoleh melalui wawancara mendalam, diskusi kelompok terfokus, observasi lapangan, dan telaah dokumen. Analisis dilakukan secara manual melalui transkripsi, pengkodean, pengelompokan tema, serta triangulasi sumber untuk memastikan validitas data. Hasil penelitian menunjukkan bahwa akademisi dan regulator memiliki persepsi positif terhadap biomining karena dinilai mendukung prinsip ekonomi sirkular dan pembangunan berkelanjutan. Masyarakat lokal menyambut biomining dengan optimisme berhati-hati, dipengaruhi pengalaman buruk dengan metode konvensional, tetapi masih menuntut transparansi dan jaminan keamanan. Sebaliknya, perusahaan tambang lebih skeptis karena mempertimbangkan risiko teknis, biaya investasi awal, dan ketidakpastian keuntungan jangka panjang. Kesimpulan penelitian ini menegaskan bahwa keberhasilan biomining bergantung pada bukti teknis yang meyakinkan, kepastian regulasi, serta legitimasi sosial melalui keterlibatan masyarakat. Sinergi triple helix antara pemerintah, industri, dan akademisi diperlukan untuk mempercepat adopsi teknologi biomining di Indonesia.

Kata kunci: Biomining, Limbah tambang, Persepsi pemangku kepentingan, Keberlanjutan, Triple helix

ABSTRACT

Mining waste management is a major challenge, resulting in water pollution, ecosystem degradation, and heavy metal accumulation. Biomining, the use of microorganisms to extract and stabilize metals, is seen as an innovative solution that is more environmentally friendly than conventional methods. This study aims to explore the perceptions of stakeholders regulators, mining companies, local communities, and academics on the application of biomining in mining waste management. The study employed a descriptive qualitative approach with a case study design. Data were obtained through in-depth interviews, focus group discussions, field observations, and document reviews. Analysis was conducted manually through transcription, coding, theme grouping, and source triangulation to ensure data validity. The results show that academics and regulators have positive perceptions of biomining because it supports the principles of a circular economy and sustainable development. Local communities welcome biomining with cautious optimism, influenced by negative experiences with conventional methods, but still demand transparency and safety assurance. Conversely, mining companies are more skeptical, considering technical risks, initial investment costs, and the uncertainty of long-term profitability. The study's conclusions emphasize that the success of biomining depends on convincing technical evidence, regulatory certainty, and social legitimacy through community engagement. Triple helix synergy between government, industry, and academia is needed to accelerate the adoption of biomining technology in Indonesia.

Keywords: Biomining, Mining waste, Stakeholder perception, Sustainability, Triple helix

INTRODUCTION

Research in the field of mining waste management continues to grow due to significant environmental impacts such as groundwater contamination, habitat degradation, and heavy metal accumulation (Environmental impact of mining, 2025). Specifically, biomining, a metal extraction technology using microorganisms or fungi, is advocated as a more environmentally friendly alternative for the recovery of tailings and mine waste. Although the technical potential of biomining has been reviewed in the biotechnology and hydrometallurgy literature (Johnson, 2014; Martínez-Bellange et al., 2022), its practical adoption in the context of mining waste management in developing countries like Indonesia remains limited. Furthermore, previous literature has focused primarily on the technical and economic effectiveness of biomining, while neglecting stakeholder perceptions, a key factor in technology adoption (Tayebi-Khorami et al., 2019). In fact, research in the biogas and mine reclamation sectors demonstrates the importance of stakeholder perceptions of sustainable governance and reclamation practices, with factors such as community engagement, transparency, and socio-economic benefits influencing acceptance (Horschig et al., 2020; Basu, 2024). Furthermore, a study in Ghana revealed varying stakeholder perceptions regarding mining sustainability performance. For example, local communities and regulators perceived the company's socio-environmental interventions as disproportionate to the economic benefits, while internal managers were satisfied with their achievements due to a lack of understanding across stakeholders (Oduro Amoako et al., 2023). Furthermore, other research identified a perception gap between the positive and negative impacts of mining, with stakeholders often differing in their perceptions of environmental and social implications (Mbachu, 2025). In Indonesia, a participatory approach to mining village development demonstrated that stakeholder perceptions of community participation play a crucial role in successful development and management (Mattalitti, 2022), while the case of mine reclamation in India emphasized that success relies heavily on community engagement, transparency, and socio-economic incentives (Basu, 2024).

Therefore, the existing research gap is: the lack of empirical studies that specifically explore stakeholder perceptions of the application of biomining in mine waste management, especially in the Indonesian context, where the urgency of managing tailings and mine waste is very high but the adoption of biomining technology is still minimal. The novelty of this research lies in its qualitative approach that places the perceptions of various stakeholder groups including local governments, mining companies, local communities, and academics at the center of the analysis, filling the gap between technical studies of biomining and passive studies on reclamation or sustainability. In addition, this approach adopts a technology perception framework and innovation adoption theory (e.g., the Technology Acceptance Model) in the context of biomining and mine environmental management. The objectives of this study are: to explore stakeholder perceptions of the application of biomining as a green innovation in mine waste management, and to identify opportunities and barriers to the adoption of this technology, so as to provide recommendations for intervention strategies ranging from policy, applied research, to local community empowerment.

Thus, this study provides both theoretical and practical contributions: first, expanding the biomining literature through stakeholder perspectives in the context of emerging economies; second, providing insights for policymakers, industry, and academics in developing a roadmap for inclusive and sustainable biomining adoption; and third, applying a proven participatory approach in sustainable mining governance

(Horschig et al., 2020; Basu, 2024) to innovative technologies such as biomining. To achieve these objectives, this study will implement qualitative methods through in-depth interviews, focus group discussions (FGDs), and internal document/publication analysis at one or more mining sites in Indonesia with initial interest in biomining. The study will explore stakeholder perceptions regarding the following aspects: environmental benefits, economic feasibility, technological readiness, regulations, and social trust. The findings of this study are expected to close the gap in practical and academic knowledge and serve as a basis for designing multi-stakeholder policies to accelerate the implementation of biomining in mine waste management. The purpose of this study is to explore and analyze the perceptions of stakeholders including the government, mining companies, surrounding communities, and academics regarding the implementation of biomining as an innovative approach in mine waste management.

METHODS

This research uses a descriptive qualitative approach with a case study design to explore stakeholder perceptions of the application of biomining in mining waste management. This approach was chosen based on the research objective, which is oriented towards an in-depth understanding of the views and experiences of actors directly involved in mining environmental issues. Research informants were selected using purposive sampling and snowball sampling techniques to ensure representation from four main groups: regulators/government, mining companies, surrounding communities, and academics/researchers. The number of participants was determined to reach data saturation, with an estimated 30–35 participants. Data collection techniques included in-depth semi-structured interviews, focus group discussions (FGDs), field observations, and document reviews such as environmental reports, policies, and company CSR documents. The entire research process was conducted with due regard to ethical aspects, including informed consent, guarantees of confidentiality, and data anonymity. The collected data were then analyzed using manual descriptive qualitative analysis. The analysis was carried out through several stages: data transcription, repeated reading, coding, categorizing, and drawing out main themes according to the research focus. The resulting themes included perceptions of the environmental benefits of biomining, technical and economic feasibility, regulatory readiness, and aspects of social legitimacy. To increase data validity and reliability, source triangulation techniques were used, comparing information from interviews, focus group discussions (FGDs), observations, and documents, as well as member checking with several key informants. The analysis results were then presented in the form of a thematic narrative outlining perception patterns, opportunities, and obstacles to biomining implementation in Indonesia.

RESULTS AND DISCUSSION

The research findings indicate that stakeholder perceptions of biomining as an alternative approach to mining waste management are quite diverse, influenced by institutional backgrounds, interests, and technical knowledge. Interviews and focus group discussions (FGDs) with four stakeholder groups regulators, mining companies, local communities, and academics revealed a general pattern: biomining is viewed as a promising environmentally friendly technology, but also raises concerns regarding technical feasibility, implementation costs, and regulatory certainty. This perception aligns with literature emphasizing that the adoption of environmental technologies in the extractive sector is highly dependent on social legitimacy and policy support (Arce-Rodríguez et al., 2021). Therefore, this section discusses the research findings

thematically, encompassing environmental and sustainability benefits, technical and economic challenges, regulatory readiness, and social dimensions involving public trust, then links them to previous literature.

In general, academics and most regulators believe that biomining has significant potential to reduce the environmental impact of mine tailings and waste. They emphasize that this biotechnology method can reduce hazardous heavy metal levels while regenerating high-value metals such as copper or nickel remaining in the waste. This view aligns with research by Rawlings and Johnson (2020), which states that biomining not only reduces remediation costs but also integrates circular economy principles into mining practices. Regulatory informants added that biomining has the potential to support Indonesia's commitment to the Sustainable Development Goals (SDGs) agenda, particularly Goal 12 on sustainable production and consumption. This is supported by research by Li, Zhang, and Wang (2023), which confirms that biomining is a strategic pathway to creating a circular economy-based extractive industry. Thus, the positive perception from academics and regulators demonstrates an awareness of the urgency of transitioning to greener technologies.

However, the study also revealed significant concerns from mining companies. Environmental and operations management assessed that biomining still faces technical and economic challenges. Some of these challenges include questions about the stability of microorganisms on a large scale, uncertainty about efficiency in Indonesia's complex geological conditions, and the need for substantial initial investment in research and bioreactor infrastructure. These concerns align with the findings of Tayebi-Khorami et al. (2019), who explained that despite biomining's promise, development costs and technical uncertainties are major barriers to its adoption. Mining companies also emphasized that global pressure to reduce their carbon footprint drives them to seek environmentally friendly solutions, but that technology adoption decisions are largely determined by long-term economic feasibility analyses. This perspective aligns with a study by Mudd (2010), which stated that any innovation in mining waste management will be difficult to implement without clear economic justification.

From the perspective of local communities, FGD results revealed an ambivalence between hopes and concerns. Communities tended to welcome the concept of biomining as a safer alternative to chemical waste treatment methods, as they had long experienced the negative impacts of acid mine drainage pollution. However, they were also suspicious of the long-term impacts of using microorganisms on an industrial scale. These concerns were driven by a lack of information and transparency from companies, as well as limited public literacy about biotechnology. This phenomenon aligns with research by Mbachu (2025), which demonstrated a perception gap between local communities and technical actors in assessing the impacts of mining. Negative perceptions can arise not from empirical evidence, but from limited access to clear and reliable information. Therefore, community perceptions of biomining must be understood as a reflection of their historical experiences with mining practices, including environmental conflicts that have occurred around mining areas.

Distribusi Persepsi Stakeholder Terhadap Biomining

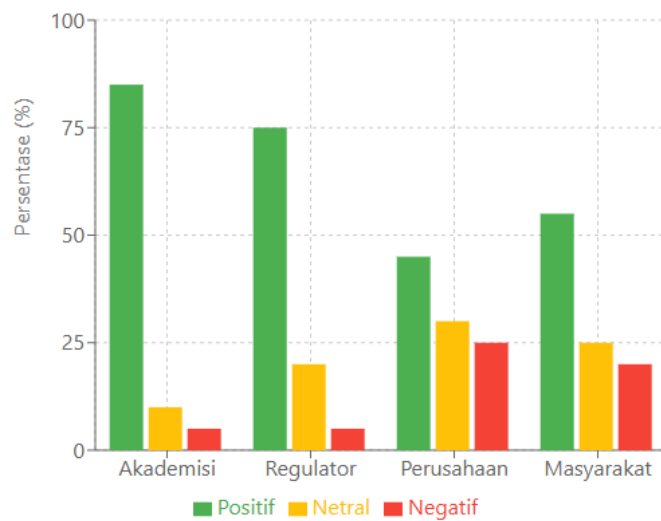


Figure 1. Stakeholder Perceptions of Biomining

The distribution of stakeholder perceptions on biomining reveals significant variation in how different stakeholder groups view the application of this technology to mine waste management. These results reflect the complexity of adopting innovative technologies in the extractive industry context, which involves multiple stakeholders with different interests and backgrounds. Academics demonstrated the most optimistic perceptions, with 85% positive responses, 10% neutral, and only 5% negative. This optimism is driven by a deep understanding of the potential of biotechnology and the view that biomining aligns with the principles of sustainability, a circular economy, and green technology development. The low negative perceptions demonstrate academics' strong confidence in the scientific validity of biomining as an innovative solution. Regulators and the government demonstrated strong support, but with practical implementation considerations, reflected in 75% positive, 20% neutral, and 5% negative perceptions. Their positive perceptions are driven by a commitment to the Sustainable Development Goals (SDGs) and an awareness of the urgency of transitioning to more environmentally friendly technologies. However, the 20% neutrality reflects regulatory caution in adopting new technologies, taking into account public policy aspects and broader socio-economic impacts. This is in line with their role as guardians of the public interest, who must ensure that every policy provides optimal benefits to the community.

Mining companies demonstrated the most skeptical perceptions, with only 45% positive, 30% neutral, and 25% negative responses. The high ambivalence (30% neutral) reflects the business dilemma facing the industry between sustainability and profitability. The 25% negative perception was driven by uncertainty about return on investment (ROI), technology and scalability risks, high initial investment costs, and the complexity of implementation within existing operations. However, the 45% positive perception reflects an awareness of Environmental, Social, and Governance (ESG) pressures and the need to adopt more sustainable practices in the long term. Local communities showed cautious optimism, with 55% positive, 25% neutral, and 20% negative perceptions. Their positive perceptions were driven by negative experiences with conventional waste management methods, hopes for safer solutions, and a desire

for environmental improvements around mining areas. However, the 45% neutral and skepticism reflect limited information about biomining technology, concerns about the long-term impacts of using microorganisms, and historical distrust of the mining industry, which has led to numerous environmental issues.

This perception distribution pattern reveals a downward gradient from academics, regulators, the public, to companies, indicating that knowledge gaps influence perceptions, proximity to implementation is inversely proportional to optimism, and risk tolerance varies across stakeholders. Interestingly, the relatively low negative perceptions (5-25%) across all groups indicate good adoption potential and the absence of total rejection from any stakeholder. This opens up a broad dialogue space for consensus building, given that all stakeholders recognize the urgency of the mining waste problem, have relatively high environmental awareness, and show interest in innovative solutions. The implication of this perception distribution is the need for different engagement strategies for each stakeholder. For companies, the focus should be on business cases, pilot projects, and risk mitigation. For the public, intensive community engagement, transparency, and a participatory approach are needed. Regulators need support in policy framework development and regulatory certainty, while academics can serve as a leverage point through research collaboration and knowledge transfer. Academic credibility can be used to convince other stakeholders, regulatory support can create an enabling environment, community acceptance can strengthen the social license to operate, and industry adoption will provide a crucial proof of concept.

Overall, this perception distribution indicates that biomining has good adoption potential in Indonesia, but requires appropriate strategies to address the existing perception gap. The success of biomining implementation will depend heavily on the ability to convert neutrality into support and reduce skepticism through concrete demonstrations of the technology's efficacy, evidence-based communication, and collaborative implementation that actively and sustainably involves all stakeholders.

An analysis of the regulatory dimensions shows that central and regional regulators acknowledge the absence of a specific legal framework for biomining implementation. Existing regulations still focus on waste quality standards, reclamation procedures, and acid mine drainage management, without including biomining as an official option. This lack of regulation is seen as a significant obstacle because it creates legal uncertainty and risks for companies seeking to adopt it. This situation is consistent with the findings of Oduro Amoako et al. (2023) in Ghana, which emphasized that stakeholder perceptions of mining sustainability are strongly influenced by regulatory legitimacy. Without clear regulations, environmental innovation tends to stop at the pilot project stage. Therefore, one recommendation emerging from regulators is the need to formulate specific policies and technical guidelines regarding biomining, including safety standards, success indicators, and economic incentive schemes. This also aligns with a study by Basu (2024), which states that the success of mine reclamation practices is determined not only by technology but also by a policy framework that supports stakeholder participation.

Discussions on social aspects and trust indicate that community legitimacy is a crucial factor in biomining implementation. Many local communities emphasize the need for direct involvement through participatory mechanisms from the early planning stages.

They desire transparency, clear communication, and assurance that biomining results will not pose new risks to the ecosystem. This finding aligns with Mattalitti's (2022) research in Sulawesi, which demonstrated that stakeholder perceptions of community participation in mine management significantly influence the success of village development around the mine. Furthermore, Horschig et al.'s (2020) study in the biogas sector emphasized that participatory governance increases stakeholder trust and accelerates the adoption of new technologies. Therefore, biomining implementation in Indonesia requires a community engagement approach that is not only informative but also collaborative, to further strengthen positive community perceptions.

Furthermore, several studies have emphasized that successful implementation of biomining on an industrial scale requires significant investment in local microbial research, bioreactor infrastructure, and comprehensive trials, leading companies to remain cautious in making investment decisions. Research by Kaksonen and van Niejenhuis (2020) emphasizes that biomining can only compete with conventional methods if there is long-term research support, optimized operating conditions, and clear policy incentives. This aligns with the doubts expressed by mining companies in this study, who questioned the return on investment (ROI) and technical risks in Indonesia's geological conditions.

Furthermore, the study findings reveal strategic opportunities from the perspective of academics and researchers. They emphasize that Indonesia has a significant microbial biodiversity, which can be utilized as a source of local microorganisms for biomining. This aligns with Johnson's (2014) study, which emphasized that the success of biomining depends heavily on the ability to develop microbial consortia suited to local geological conditions. This potential could reduce dependence on imported technology and increase national research independence. However, academics also highlight that biomining research in Indonesia still lacks support, both in terms of funding and international collaboration. Therefore, they believe that synergy between universities, research institutions, the government, and industry is key to accelerating the development of biomining based on local potential. The study also demonstrates a consensus among stakeholders on the need for cross-sector collaboration in biomining applications. Regulators emphasize the importance of policy formulation involving industry and academia, while companies believe that research support from universities can help reduce internal research costs. The public also expects a communication forum that allows them to participate in decision-making. This aligns with the triple helix model, which emphasizes government-industry-academia collaboration as a prerequisite for successful technological innovation (Etzkowitz & Zhou, 2017). In the biomining context, such collaboration not only accelerates technology adoption but also strengthens its social legitimacy. Thus, positive stakeholder perceptions can be mobilized into social capital, crucial for successful implementation.

Furthermore, community trust in biomining relies heavily on active involvement from the early stages of a project. According to Hilson (2018), social legitimacy in mining practices can only be achieved if companies involve communities in decision-making, provide transparent environmental data, and ensure tangible benefits are felt by the community. This perspective reinforces research findings that local communities around mines are cautiously optimistic but demand transparency and assurances of ecosystem sustainability.

Overall, the results of this study confirm that stakeholder perceptions of biomining form a complex spectrum of hopes and concerns. On the one hand, there is strong recognition of potential environmental benefits, a circular economy, and research opportunities. On the other hand, there are real barriers in the form of technical uncertainty, initial costs, and regulatory gaps. This aligns with the argument of Sari, Nugroho, and Wulandari (2021) that mining waste management always faces a dilemma between technical needs, costs, and social legitimacy. Therefore, to answer the research objectives, it can be concluded that the successful implementation of biomining in Indonesia depends heavily on a combination of three main factors: convincing technical evidence, supporting regulatory certainty, and social trust built through community participation.

CONCLUSION

This study confirms that stakeholder perceptions of biomining for mine waste management continue to range from high optimism to cautious skepticism. Academics and regulators demonstrate the most positive perceptions, emphasizing biomining's potential for reducing pollution, supporting circular economy principles, and aligning with the sustainable development agenda. Local communities demonstrate cautious optimism influenced by negative experiences with conventional methods, despite limited information and concerns about long-term impacts. Conversely, mining companies tend to be more skeptical, considering technical risks, high investment costs, and uncertain economic returns. These results demonstrate that the success of biomining in Indonesia is determined not only by technical evidence and economic potential, but also by regulatory legitimacy and social trust built through community engagement. Key barriers, such as the lack of specific regulations, initial cost risks, and technical skepticism, need to be addressed through clear policy formulation, evidence-based pilot projects, and cross-sectoral research support. Synergy between government, industry, academia, and the community within a triple helix framework, is a crucial prerequisite for strengthening acceptance and accelerating the adoption of this technology. Thus, this study answers the main objective of exploring stakeholders' perceptions of biomining, while also confirming that the future of sustainable mining waste management depends heavily on multi-stakeholder collaboration, transparency, and the courage to take innovative steps in the transition to green technology.

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