

# A Quantitative ESG-Based Framework for Evaluating Tailings Reprocessing and Resource Recovery

Abeer Sajid<sup>1</sup>, Seyed Mostafa Taghavi<sup>1</sup>, Moeen Hamed<sup>1</sup>,  
Hernán Antico<sup>1</sup>, Marc Bascompta<sup>1</sup>

<sup>1</sup>Department of Mining, Industrial and ICT Engineering,  
Universitat Politècnica de Catalunya (UPC) – Barcelona Tech, 08242, Spain

## Abstract

Mine tailings pose environmental risks but also offer a secondary source of critical raw materials for the energy transition. Conventional tailings reprocessing assessments focus mainly on metal recovery, often overlooking environmental, social, and governance (ESG) considerations. This study presents a quantitative ESG-based framework that integrates measurable indicators within the Analytic Hierarchy Process (AHP) to generate a Composite ESG Index for systematic project evaluation. The primary contribution is the framework itself: a quantitative, AHP-weighted ESG evaluation structure with geometric aggregation preventing compensatory masking of critical failures, anchored scoring rubrics for social and governance indicators, and a recalibration protocol enabling jurisdictional transfer. An illustrative application using secondary data from Chilean tailings operations demonstrates that water protection, carbon emission reduction, and energy demand receive high priority under Chilean mining conditions.

**Keywords:** Critical raw materials, analytic hierarchy process, indicator weighting, mine waste management, composite sustainability index

## Introduction

The global mining industry faces a dual challenge of addressing the environmental legacy of past operations while meeting the rising demand for critical materials essential for the energy transition (Kursunoglu, 2025). Mine tailings present persistent risks, including catastrophic dam failures such as those at Mount Polley (2014), Fundão (2015) and Brumadinho (2019) resulted in loss of life, extensive environmental damage, and long-term disruptions to communities (Samadi *et al.*, 2025). Beyond structural instabilities, tailings are major sources of acid mine drainage and long-term land degradation, leading to widespread contamination of ecosystems and posing serious threats to human health (Araya *et al.*, 2020).

These environmental and social consequences emphasize the need for more integrated management approaches that move beyond risk mitigation toward responsible and sustainable resource recovery. At the same time, declining global primary ore

grades are reshaping resource strategies. Historical mine tailings often contain higher concentrations of valuable metals than many newly exploited deposits, positioning tailings reprocessing as both a remediation strategy and a strategic resource opportunity (Alajoki *et al.*, 2024). This dual role, risk reduction and resource recovery, demands a more systematic and sustainability-oriented evaluation framework.

Despite progress in mining sustainability assessment, no unified quantitative framework currently exists to specifically evaluate ESG performance in tailings reprocessing projects. While circular economy principles and the 3R approach (reduce, reuse, recycle) support resource recovery and waste minimization, a structured method to quantitatively assess ESG performance within this context remains underdeveloped (Segura-Salazar *et al.*, 2019). The study addresses this gap by developing and applying a quantitative ESG-based framework to systematically evaluate tailings reprocessing alternatives. The framework's

primary contribution is a literature-informed AHP weight set for tailings reprocessing ESG evaluation, calibrated to the Chilean context and aligned with the Global Industry Standard on Tailings Management (GISTM), which constitutes the main new research output of this study. Four structural advances underpin this contribution: an AHP-weighted indicator hierarchy purpose-built for tailings reprocessing scope; geometric aggregation that reduces excessive pillar-level compensability; anchored scoring rubrics for social and governance indicators; and a recalibration protocol enabling transfer to other jurisdictions without structural change.

## Methods

### Analytic Hierarchy Process

Analytic Hierarchy Process methodology is applied to determine the relative weights of the selected ESG indicators. Indicator weights are derived from a structured literature-informed judgment process, drawing on published Chilean tailings ESG priorities, decarbonisation targets, and regional water scarcity constraints (Araya *et al.*, 2020; Garcia-Zavala *et al.*, 2023; Luo *et al.*, 2024). This approach follows established practice for methodological framework papers in mining sustainability research (Bascompta *et al.*, 2022; Garcia-Zavala *et al.*, 2023). Weights are presented as an illustrative configuration intended for recalibration by practitioners using site-specific expert input. The relative importance of each criterion against every other is assessed based on Saaty's 9-point fundamental scale (Luo *et al.*, 2024). Because indicators are expressed in heterogeneous units, tCO<sub>2</sub>e, kWh/t, m<sup>3</sup>, ha, and ordinal scores, all raw values are rescaled to a common [0,1] interval using min-max normalisation (Pollesch and Dale, 2016). For positive indicators:

$$x'_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}}$$

For negative indicators such as GHG emissions and LTIFR:

$$x'_{ij} = \frac{x_{max} - x_{ij}}{x_{max} - x_{min}}$$

ensuring a score of 1 always represents best ESG performance. Boundary values for normalisation were defined as follows. For GHG emissions and energy demand, maximum values were set at the highest reported figures across comparable Chilean tailings reprocessing operations, with minimum values representing best available technology benchmarks reported in the literature (Araya *et al.*, 2020; Garcia-Zavala *et al.*, 2023). For water consumption, boundaries reflect the range of specific water consumption reported across hyperarid mining operations in the Atacama and Antofagasta regions (Garcia-Zavala *et al.*, 2023). For land rehabilitation, minimum and maximum values correspond to the lowest and highest percentage reductions in disturbed land area reported in peer-reviewed Chilean tailings studies (Araya *et al.*, 2020). For safety, the 2024 ICMM industry-average TRIFR of 2.29 serves as the normalisation benchmark, with zero representing best achievable performance. For stakeholder engagement and transparency, boundaries correspond to the GRI defined scoring rubric endpoints: 0 representing absent or unverifiable performance and the maximum score representing full compliance with all defined criteria. For regulatory compliance, boundary values are defined by the rubric itself, ranging from 0% to 100% adherence, with targets aligned to national and international mining standards (Anani *et al.*, 2025). The weighted indicators are then aggregated into a Composite ESG Index using weighted geometric aggregation expressed in logarithmic form for each reprocessing alternative under evaluation (Munda, 2005; OECD *et al.*, 2008). The ESG Index for alternative  $j$  is calculated as equation 1.

$$ESG\ Index_j = \exp\left(\sum_{i=1}^n w_i \times \ln(x'_{ij} + \epsilon)\right) \quad (1)$$

where  $w_i$  is the global weight of indicator  $i$ ,  $x'_{ij}$  is the normalised score of indicators  $i$  for alternative  $j$ , and  $\epsilon$  is a small constant introduced to avoid undefined logarithmic values when normalised scores equal zero. In this study,  $\epsilon = 0.001$  was used. This value



is small relative to the 0–1 normalised scale and preserves the penalty for very low indicator scores.

Weighted geometric aggregation, expressed in logarithmic form, was selected over additive weighted averaging because it reduces full compensability among ESG indicators. In an additive index, strong performance in some indicators can offset very poor performance in others, even when the weak indicator represents a critical risk. This is problematic for tailings reprocessing, where poor performance in areas such as water protection, safety, regulatory compliance, or tailings facility integrity may have severe and potentially irreversible consequences. Under the logarithmic aggregation structure, a very low normalised score produces a strong penalty in the overall index, limiting the ability of high scores in other indicators to compensate for critical weaknesses. This aggregation approach is therefore more suitable than additive weighted averaging for evaluating tailings reprocessing alternatives involving potentially catastrophic or irreversible ESG risks (Munda, 2005; OECD et al., 2008).

### Quantifiable ESG Indicators

Indicators were selected based on established international sustainability reporting guidelines, relevant regulatory requirements including those from the EU, and systematic review of peer-reviewed tailings sustainability literature, to ensure both comprehensiveness and local relevance. The chosen indicators are designed to be quantifiable and reflective of critical performance aspects across all three ESG dimensions. For each indicator the following information is provided: indicator name, measurement unit, preference scale (indicate a better performance for lower or higher indicator values), and a short description.

The environmental dimension comprises four indicators that relate to greenhouse gas emissions, energy demand, water consumption and land rehabilitation.

**Greenhouse Gas Emissions:** GHG emissions are quantified in CO<sub>2</sub> equivalents (tCO<sub>2</sub>e) using standard life cycle assessment methodologies for energy consumption, process chemicals, and transportation activities. This involves calculating Scope 1 (direct

emissions), Scope 2 (indirect emissions from purchased energy), and relevant Scope 3 (other indirect emissions) emissions, acknowledging that improved recovery can reduce GHG emissions (Araya et al., 2020; Padilla-Rivera et al., 2025).

**Energy Demand:** Energy demand is measured as energy intensity, expressed in kilowatt-hours per tonne (kWh/t) or gigajoules per tonne (GJ/t) of reprocessed material. This metric accounts for all forms of energy consumption, including electricity, heat, and fuel, during the reprocessing stages (Araya et al., 2020; Bascompta et al., 2022; Karu and Kekkonen, 2025).

**Water Consumption:** Water consumption is evaluated using metrics such as cubic meters of water recovered (m<sup>3</sup>), the percentage of process water recycled (%) within the operation, and specific water consumption per tonne of material processed. Emphasis is placed on minimizing fresh water intake and maximizing reuse for re-mining, especially in hyperarid locations (Araya et al., 2020; Garcia-Zavala et al., 2023).

**Land Rehabilitation:** This is quantified by the area of land restored in hectares (ha), the percentage reduction in disturbed land area post-reprocessing, and the measured increase in biodiversity indices. These metrics assess the ecological recovery and future land use potential following reprocessing activities, often aiming to improve environmental safety and reduce site rehabilitation costs (Karu and Kekkonen, 2025; Kursunoglu, 2025).

The indicators in the social dimension integrate different societal aspects like employment, safety and stakeholder engagement.

**Employment:** This is measured by the number of local jobs created or maintained, the percentage of local hires in skilled and unskilled positions, and the financial investment in local skills development and training programs, often considering the unemployment rate of a community (Bascompta et al., 2022).

**Safety:** Safety performance is measured using industry-standard metrics such as the LTIFR and TRIFR, both expressed per million hours worked per the ICMM safety protocol.

**Stakeholder Engagement:** Stakeholder engagement is quantified through an index based on the frequency and quality of



interactions (e.g., public meetings, workshops), the number and resolution rate of recorded grievances, and the extent of participatory decision-making instances, scored on the five-level IAP2 Public Participation Spectrum (1=Inform, 2=Consult, 3=Involve, 4=Collaborate, 5=Empower), with each level requiring documented evidence to be assigned. This index is derived from structured interviews, surveys, and content analysis of engagement records, with a focus on prioritizing stakeholder concerns and values (Manjengwa *et al.*, 2023; Nehring and Knights, 2024). While ordinal in nature, this scoring approach is compatible with AHP-based composite indexing when anchor points are explicitly defined and consistently applied across all evaluated alternatives (Ishizaka and Labib, 2011).

The indicators of the governance dimension reflect the political and regulatory environment.

**Regulatory Compliance:** This is assessed by the percentage (%) of adherence to environmental and social regulations, with a target of zero instances of non-compliance, demonstrating commitment to national and international standards. This includes adherence to corporate policies and international mining standards (Di Guimarães *et al.*, 2025).

**Transparency:** Transparency is evaluated by the clarity and accessibility of project information to stakeholders, and the demonstrable robustness and effectiveness of grievance mechanisms, scored against a seven-item GRI 102 disclosure checklist (0=absent, 1=present and verifiable), rescaled to [0,1]. This includes public reporting and clear communication strategies (Jagrič *et al.*, 2025; Padilla-Rivera *et al.*, 2025). Similarly, the GRI 102 checklist scoring is ordinal but consistently anchored, ensuring comparability across alternatives within the same evaluation (Ishizaka and Labib, 2011).

### Framework demonstration using secondary data

Chile is selected as a critical case: it produces approximately 24% of global mined copper, hosts over 740 registered tailings storage facilities, and operates predominantly in the

Atacama and Antofagasta regions where 93% of mining operations face high or very-high water scarcity risk (Cacciuttolo and Atencio, 2022; Garcia-Zavala *et al.*, 2023). This concentration of tailings volume, water stress, and decarbonisation pressure represents the most demanding available test context for the proposed framework. Following established practice for methodological framework papers in mining ESG research (Bascompta *et al.*, 2022; Garcia-Zavala *et al.*, 2023), the framework is demonstrated through illustrative validation using secondary data compiled from peer-reviewed tailings reprocessing studies in Chile and comparable contexts (Araya *et al.*, 2020; Garcia-Zavala *et al.*, 2023; Luo *et al.*, 2024). The original contribution of this conference paper lies in the development, calibration, and illustrative application of the ESG evaluation framework, rather than in the generation of new primary field measurements. Primary field validation across multiple jurisdictions is identified as the next research phase to further strengthen transferability. The objective is to demonstrate four framework properties: discriminant capacity, non-compensatory behaviour, contextual weight sensitivity, and diagnostic utility. The demonstration assessed whether the selected indicators appropriately reflect sustainability priorities in the Chilean context and whether the weighting distribution aligns with prevailing ESG challenges, such as water scarcity, energy intensity, decarbonisation targets and regulatory oversight. Indicator values reported in the literature were normalised to ensure comparability across different scales, allowing consistent integration within the Composite ESG Index structure. The resulting weighting distribution is presented in Table 1.

Global Weights represent the final contribution of each indicator to the Composite ESG Index. The distribution reflects that in the Chilean context, environmental factors associated with energy and emissions carry the highest priority to ensure that tailings reprocessing contributes to national decarbonisation goals (Adrianto and Pfister, 2022; Luo *et al.*, 2024). Land Rehabilitation and Water Consumption



**Table 1** ESG Dimension, indicators, and the weights of the ESG framework applied to the Chilean tailings reprocessing context (Garcia-Zavala et al., 2023)

Dimensions	Indicators	Weights (%) per dimension	Weights (%) per Indicator	Global Weight (%)
Environmental	GHG emission	70	34.3	24
	Energy demand		28.6	20
	Water consumption		18.6	13
	Land rehabilitation		18.5	13
Social	Safety	25	50	12.5
	Stakeholder engagement		30	7.5
	Employment		20	5
Governance	Regulatory compliance	5	70	3.5
	Transparency		30	1.5

follow, which is a reflection of the industry’s need to address long-term geotechnical liabilities and the extreme water scarcity prevalent in the Atacama and Antofagasta region (Araya et al., 2020; Luo et al., 2024).

Within the social dimension, safety is prioritized as the most critical indicator to prevent catastrophic tailings failure and ensure a safe workplace (Kursunoglu, 2025). This is followed by Stakeholder Engagement and Employment, ensuring that reprocessing initiatives maintain a social license to operate by providing local community benefits and resolving grievances (Garcia-Zavala et al., 2023; Nehring and Knights, 2024). Governance factors are distributed between Regulatory Compliance and Transparency, serving as essential thresholds for institutional accountability and public reporting (Garcia-Zavala et al., 2023; Karu and Kekkonen, 2025).

Quantitative aggregation of these indicators reveals a critical trade-off inherent in the Chilean context. The transition to energy-intensive water solutions, such as desalination, to address local scarcity can increase the energy demand and GHG components of the index. However, the framework can identify whether such trade-offs are offset by improvements in long-term geotechnical liability reduction and land-footprint reduction (Adrianto and Pfister, 2022; Araya et al., 2020). The application

confirms all four properties: the framework produces differentiated scores, geometric aggregation penalises critical weaknesses, the weight distribution reflects Chilean priorities, and pillar-level sub-scores provide diagnostic information. Empirical validation using primary field data constitutes the next research phase.

**Conclusions**

This study developed and demonstrated a quantitative ESG-based framework for the evaluation of tailings reprocessing. By integrating measurable environmental, social, and governance indicators within the Analytic Hierarchy Process (AHP), the research generated a Composite ESG Index that enables comparative assessment of resource recovery options. The framework addresses a critical gap in tailings reprocessing evaluation, where technical and economic criteria have traditionally dominated while ESG dimensions remained secondary considerations.

Results demonstrate that environmental indicators, particularly greenhouse gas emissions, energy intensity, and water consumption, carry the greatest influence in the Chilean context, reflecting national decarbonisation goals and regional water scarcity constraints. At the same time, social and governance dimensions, especially safety



and regulatory compliance, function as essential boundary conditions for responsible operation.

The framework is adaptable to different regulatory and geographical contexts through recalibration of indicator weights, enhancing its broader applicability. This research advances the operationalization of ESG principles in tailings reprocessing by aligning resource recovery with water protection, emissions reduction, and institutional accountability. The framework has three limitations: the weight configuration is Chilean-specific and requires recalibration for other jurisdictions using the protocol described herein; social and governance indicators rely on anchored ordinal scoring rather than continuous measurement; and the application uses secondary data, with primary field validation across multiple jurisdictions constituting the critical next research phase.

## Acknowledgements

This research has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Actions Doctoral Network (HORIZON-MSCA-2023-DN-01) within the CRITERIA Project (Grant No. 101169238). The authors gratefully acknowledge this financial support and the institutional support of Universitat Politècnica de Catalunya. The authors also thank all co-organisers for hosting the IMWA 2026 Conference.

## References

Adrianto, L.R., Pfister, S., 2022. Prospective environmental assessment of reprocessing and valorization alternatives for sulfidic copper tailings.

Alajoki, J., Karppinen, A., Rinne, T., Serna-Guerrero, R., Lundström, M., 2024. Leaching strategies for the recovery of Co, Ni, Cu and Zn from historical tailings. *Miner. Eng.* 217, 108967. <https://doi.org/10.1016/j.mineng.2024.108967>

Anani, A., Adewuyi, S.O., Gonzales, C.G., 2025. Sustainable copper supply chains: Evaluating ESG risks through the lens of regulatory compliance and risk assessment strategies. *Extr. Ind. Soc.* 23. <https://doi.org/10.1016/j.exis.2025.101662>

Araya, N., Kraslawski, A., Cisternas, L.A., 2020. Towards mine tailings valorization: Recovery of critical materials from Chilean mine tailings. *J. Clean. Prod.* 263, 121555. <https://doi.org/10.1016/j.jclepro.2020.121555>

Bascompta, M., Sanmiquel, L., Vintró, C., Yusefian, M., 2022. Corporate Social Responsibility Index for Mine Sites. *Sustainability* 14, 13570. <https://doi.org/10.3390/su142013570>

Cacciuttolo, C., Atencio, E., 2022. Past, Present, and Future of Copper Mine Tailings Governance in Chile (1905–2022): A Review in One of the Leading Mining Countries in the World. *Int. J. Environ. Res. Public. Health* 19, 13060. <https://doi.org/10.3390/ijerph192013060>

Di Guimarães, L., Araújo, U.P., Lima, H.M.D., 2025. Mine closure transparency and disclosure: An open-source evaluation of financial, technical, and social reporting. *Resour. Policy* 107. <https://doi.org/10.1016/j.resourpol.2025.105644>

Garcia-Zavala, C., Ordens, C.M., Pagliero, L., Lèbre, É., Aitken, D., Stringer, M., 2023. An approach for prioritising environmental, social and governance (ESG) water-related risks for the mining industry: The case of Chile. *Extr. Ind. Soc.* 14. <https://doi.org/10.1016/j.exis.2023.101259>

Ishizaka, A., Labib, A., 2011. Review of the main developments in the analytic hierarchy process. *Expert Syst. Appl.* S0957417411006701. <https://doi.org/10.1016/j.eswa.2011.04.143>

Jagrič, T., Mumel, D., Skaza, A., 2025. Evaluation of Environmental, Social, and Governance Risks? A Critical Literature Review with Practical Implications. *Sustainability* 17, 8451. <https://doi.org/10.3390/su17188451>

Karu, V., Kekkonen, A., 2025. Integrating ESG and Sustainability in the Raw Materials Sector, in: *Environ. Technol. Resour. - Proc. Int. Sci. Pract. Conf. RTU PRESS*, pp. 267–274. <https://doi.org/10.17770/etr2025vol1.8692>

Kursunoglu, S., 2025. A Review on the Recovery of Critical Metals from Mine and Mineral Processing Tailings: Recent Advances. *J. Sustain. Metall.* 11. <https://doi.org/10.1007/s40831-025-01126-y>

Luo, C., Liu, Y., Pan, L., Yang, F., 2024. Navigating mineral policy development challenges in the global south using analytic hierarchy process. *Resour. Policy* 90. <https://doi.org/10.1016/j.resourpol.2024.104797>

Manjengwa, E.R., Dorfling, C., Tadie, M., 2023. Development of a conceptual framework to evaluate factors that affect drivers for stakeholder engagement in mine waste management. *Resour. Policy* 81, 103280. <https://doi.org/10.1016/j.resourpol.2022.103280>

Munda, G., 2005. "Measuring Sustainability": A Multi-Criterion Framework. *Environ. Dev. Sustain.* 7, 117–134. <https://doi.org/10.1007/s10668-003-4713-0>

Nehring, M., Knights, P., 2024. A Systems Engineering Approach to Incorporate ESG Risks and Opportunities in Early-Stage Mine Design and Planning. *Mining* 4, 546–566. <https://doi.org/10.3390/mining4030031>



- OECD, European Union, Joint Research Centre - European Commission, 2008. Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD. <https://doi.org/10.1787/9789264043466-en>
- Padilla-Rivera, A., Hannouf, M., Assefa, G., Gates, I., 2025. Enhancing environmental, social, and governance, performance and reporting through integration of life cycle sustainability assessment framework. *Sustain. Dev.* 33, 2975–2995. <https://doi.org/10.1002/sd.3265>
- Pollesch, N.L., Dale, V.H., 2016. Normalization in sustainability assessment: Methods and implications. *Ecol. Econ.* 130, 195–208. <https://doi.org/10.1016/j.ecolecon.2016.06.018>
- Samadi, M., Gilani, S.-O., Abdollahisharif, J., Bakhtavar, E., 2025. Towards sustainable mine closure and reclamation through strategic tailing disposal sites evaluation: A causality-based Dempster-Shafer framework. *Resour. Policy* 108, 105676. <https://doi.org/10.1016/j.resourpol.2025.105676>
- Segura-Salazar, J., Lima, F.M., Tavares, L.M., 2019. Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *J. Clean. Prod.* 232, 174–192. <https://doi.org/10.1016/j.jclepro.2019.05.318>