Identifying the Sustainability Efficiency Peak in Tailings Reprocessing: An Entropy–TOPSIS Assessment of Restorative Mining

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Abstract

Reprocessing of historical sulfidic tailings is evaluated as a circular economy strategy using a multi-criteria decision-making framework. Using Entropy-TOPSIS, six reprocessing alternatives were analyzed integrating technical, economic, environmental, and social indicators. Results identify 80% tailings reprocessing as the sustainability-optimal restorative mining pathway, achieving a closeness coefficient of 0.844. Although full reprocessing maximizes copper recovery, exponential increases in freshwater stress and community disturbance penalize performance. Findings reveal a non-monotonic relationship between reprocessing intensity and sustainability. Moderate reprocessing provides a resilient balance between resource efficiency and regional socio-environmental stability.

Keywords: Restorative mining, circular economy, tailings reprocessing

Introduction

Strategic European policy initiatives now frame mine tailings as vital secondary resource reservoirs rather than mere environmental liabilities (European Commission 2023). Such a paradigm shift is essential, given that annual global production of mineral waste exceeds 10 billion tonnes (Araya et al. 2020; Johansson *et al.* 2024). Reprocessing these deposits represents a restorative mining strategy capable of mitigating acid mine drainage (AMD) and reducing reliance on primary extraction (Blannin *et al.* 2023; Kursunoglu 2025). Evaluating the viability of tailings re-mining requires balancing technical feasibility, economic performance, and environmental-social impacts through structured sustainability assessment frameworks integrating multi-dimensional indicators (Adiansyah et al. 2015; Figueiredo *et al.* 2019; Bascompta *et al.* 2025). Current decision-making often lacks formal quantitative models that integrate environmental, social, and governance (ESG) metrics directly into strategic planning. This absence of a structured multi-dimensional framework creates uncertainty in determining the most sustainable operating scale for secondary resource projects (Araya et al. 2021).

To address this gap, this study introduces an integrated multi-criteria decision-making (MCDM) framework based on technical, economic, environmental, and social (TEES) dimensions. Objective indicator weights are derived using the Entropy method, while strategic alternatives are ranked through the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Jiang *et al.* 2020; Kaneesamkandi *et al.* 2020). To demonstrate its practical applicability, the proposed framework is applied to a large-scale historical tailings facility in the Iberian Pyrite Belt (Spain).

Central to this research is determining the sustainability-optimal level of historical tailings reprocessing and evaluating whether sustainability increases proportionally with extraction intensity or if intermediate reprocessing provides a more balanced trade-off.

Research boundaries are limited to a site-specific assessment under current technological and regulatory conditions. Conventional flotation is assumed as the reference processing technology, and copper represents the primary recovered product. Results represent a strategic evaluation of defined scenarios ranging from 0–100% tailings reprocessing.

Methods

This study applies a structured multi-criteria decision-making (MCDM) framework to evaluate the sustainability of historical tailings reprocessing at Atalaya Mining within the Iberian Pyrite Belt. The assessment utilizes a site-specific database derived from Atalaya Mining's 2023–2025 Sustainability Reports and the Proyecto Riotinto NI 43-101 Technical Report (Noble *et al.* 2018; Noble 2022; Atalaya Mining Plc 2023, 2024, 2025). This ensures that the 14 indicators across technical, economic, environmental, and social (TEES) dimensions reflect the real-world operational constraints of the Iberian Pyrite Belt. All objective weighting and ranking were performed via the Entropy-TOPSIS method implemented in Microsoft Excel.

Scenario Definition

Six discrete alternatives (A0–A5) represent varying degrees of tailings reprocessing, ranging from a "no-action" baseline (A0) to 100% full reprocessing (A5) (Table 1). These scenarios assume proportional scaling of operational flows based on the percentage of tailings treated.

Indicator Selection and Justification

Fourteen indicators across technical, economic, environmental, and social (TEES) dimensions were operationalized to reflect site-specific risks and strategic priorities (Table 2). Indicators were selected based on reliable site-specific data availability and operational relevance (Noble *et al.* 2018; Atalaya Mining Plc 2023, 2024, 2025), ensuring methodological transparency while avoiding speculative assumptions. Technical indicators (T1–T2) capture resource recovery efficiency and geotechnical safety factor improvements in alignment with the Global Industry Standard on Tailings Management (GISTM). Economic indicators (E1–E3) evaluate net present value (NPV), capital expenses (CAPEX), and operational efficiency (OPEX), while environmental indicators (ENV1–ENV5) address regional water scarcity, electricity demand, carbon footprint, and acid mine drainage (AMD) load reduction. Social indicators (S1–S4) measure employment generation, social investment, heritage conservation, and a community disturbance index representing noise and traffic effects.

Although certain indicators may exhibit operational correlation (e.g., electricity demand and carbon emissions), they represent distinct sustainability dimensions and were therefore retained to capture independent environmental pressures within the TEES framework.

Indicators were calculated on a project-life basis, assuming proportional scaling of material throughput, energy demand, water consumption, and associated operational flows across reprocessing scenarios. To ensure a strict evaluation of regional impacts, the analysis incorporates site-specific environmental constraints, including a regional freshwater concession limit of 4.93 $Mm^3/year$. This is operationalized by applying an exponential stress factor ($x^{1.2}$) to scenarios approaching or exceeding this

Table 1 *Definition of reprocessing alternatives.*

Alternative	Tailings Reprocessed (%)	Description
A0	0	No action – environmental liability
A1	20	Very low reprocessing
A2	40	Low reprocessing
A3	60	Medium reprocessing
A4	80	High reprocessing
A5	100	Full reprocessing

Table 2 *Indicator system and TEES framework parameters.*

Dimension	Code	Indicator	Unit	Benchmark	Rationale
Technical	T1	Copper recovery	kt	52.3 (Atalaya Mining Plc 2023)	Reflects resource recovery efficiency and contribution to supply
	T2	TSF safety factor improvement	–	1.88 (Global Tailings Review 2020; Noble 2022; Atalaya Mining Plc 2023)	Indicates geotechnical risk reduction
Economic	E1	CAPEX	$ M	94.90 (Noble *et al.* 2018)	Represents upfront investment requirement
	E2	OPEX	$/t	6.13 (Noble 2022)	Reflects operational efficiency
	E3	NPV (10% rate)	$ M	915 (Ramírez Rodríguez 2023)	Measures long-term financial viability
Environmental	ENV1	Total water intensity	m^3/t	1.91 (Atalaya Mining Plc 2025)	Captures regional water pressure
	ENV2	Electricity intensity	kWh/t	22.66 (Atalaya Mining Plc 2025)	Reflects energy demand
	ENV3	Carbon footprint	t CO_2-eq	98,447 (Noble 2022)	Indicates greenhouse gas emissions
	ENV4	AMD load reduction	%	Proportional to the reprocessed tailings	Reflects mitigation of acid mine drainage risk
	ENV5	Freshwater withdrawal	m^3/t	0.22 (Atalaya Mining Plc 2025)	Measures freshwater consumption
Social	S1	Total employment influence	jobs	2,355 (Atalaya Mining Plc 2023)	Measures local job creation
	S2	Social investment	$ k/y	1,107 (Atalaya Mining Plc 2025)	Indicates community development contribution
	S3	Heritage conservation	M$	3.11 (Atalaya Mining Plc 2023)	Reflects cultural preservation contribution
	S4	Community disturbance	-	index	Captures local nuisance and disruption

threshold to reflect increased water scarcity risk. Benchmark values were proportionally scaled across the six reprocessing scenarios (A0–A5).

Entropy Weight Method (EWM) and TOPSIS Ranking Procedure

Objective indicator weights were determined using the Entropy Weight Method (EWM) to eliminate subjective bias. Shannon entropy theory evaluates the dispersion of each indicator across alternatives; indicators with greater variability provide more discriminatory information and receive higher weights (Kaneesamkandi *et al.* 2020). Raw data were standardized into dimensionless values using min–max normalization for benefit-type and cost-type indicators (Kaneesamkandi *et al.* 2020). Computation of entropy values utilized the normalized TEES indicator matrix derived from the scenario dataset for the six reprocessing alternatives (A0–A5).

Subsequent ranking was performed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). This procedure identifies the optimal alternative by calculating the Euclidean distance from both the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) (Adibi *et al.* 2015; Jiang *et al.* 2020). Relative closeness coefficients (C_i) ranging from 0 to 1 were determined for each scenario, where higher values indicate superior multi-dimensional sustainability performance (Kaneesamkandi *et al.* 2020).

Table 3 Entropy weights and objective indicator utility.

Code	Indicator	Type	Σ(yij)	Entropy (Ej)	Utility (dj)	Weight (Wj)
T1	Copper recovery	Benefit	3.006	0.8327	0.1673	7.16%
T2	TSF safety factor improvement	Benefit	3.008	0.8351	0.1649	7.06%
E1	CAPEX	Cost	2.435	0.9084	0.0916	3.92%
E2	OPEX	Cost	3.006	0.8327	0.1673	7.16%
E3	NPV (10% rate)	Benefit	3.006	0.8327	0.1673	7.16%
ENV1	Total water intensity	Cost	3.284	0.8041	0.1959	8.38%
ENV2	Electricity intensity	Cost	3.175	0.8149	0.1851	7.92%
ENV3	Carbon footprint	Cost	3.272	0.8052	0.1948	8.33%
ENV4	AMD load reduction	Benefit	3.006	0.8327	0.1673	7.16%
ENV5	Freshwater withdrawal	Cost	3.472	0.7853	0.2147	9.19%
S1	Total employment influence	Benefit	3.105	0.8224	0.1776	7.60%
S2	Social investment	Benefit	3.324	0.8001	0.1999	8.55%
S3	Heritage conservation	Benefit	3.402	0.7932	0.2068	8.85%
S4	Community disturbance	Cost	3.008	0.8711	0.1289	5.52%
Total					2.3364	100.00%

Results and Discussion

Entropy analysis quantifies the objective information utility of each indicator based on its dispersion across the six reprocessing scenarios (Table 3). The weighting structure indicates that environmental and social indicators exert the strongest influence within the decision framework. Freshwater withdrawal (ENV5) receives the highest weight (9.19%), reflecting both its strong variability across scenarios and the operational sensitivity of the Iberian Pyrite Belt to water resource constraints (Rosario-Beltré *et al.* 2023). Social indicators, particularly heritage conservation (S3, 8.85%) and social investment (S2, 8.55%), also demonstrate high discriminatory power, emphasizing the importance of socio-cultural considerations in long-term tailings management strategies.

Environmental indicators related to electricity demand and carbon emissions (ENV2–ENV3) maintain consistently high influence, confirming that resource and energy intensity are critical constraints for large-scale reprocessing systems. In contrast, CAPEX (E1) receives the lowest weight (3.92%), indicating comparatively lower variability between alternatives and suggesting that long-term operational and environmental trade-offs dominate over initial investment costs within the entropy-based framework. Geotechnical stability (T2) retains moderate influence (7.06%), ensuring that alignment with the Global Industry Standard on Tailings Management (GISTM) remains integrated into the sustainability assessment.

Defining A0 ("No Action") as the baseline demonstrates that maintaining an untreated TSF is not a neutral pathway; its negative NPV (–$74.1 M) (Noble *et al.* 2018), zero material recovery, and lack of safety improvements result in a closeness coefficient of 0.000 (Rank 6). This outcome highlights tailings reprocessing as a liability-reduction strategy rather than solely a production-oriented activity.

Alternative A4 (Ci = 0.844) represents the optimal sustainability balance within the evaluated system. The scenario achieves substantial copper recovery and significant TSF stabilization benefits while avoiding the disproportionate increases in freshwater demand and electricity consumption observed under full-scale reprocessing. Consequently, A4 maintains the most favorable balance between the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) within the entropy–TOPSIS framework. Although

***Table 4** Entropy-weighted TOPSIS ranking of reprocessing scenarios.*

Alternative	Tailings Reprocessed	C_1	Rank
A4	80%	0.844	1
A3	60%	0.754	2
A5	100%	0.741	3
A2	40%	0.560	4
A1	20%	0.330	5
A0	0%	0.000	6

***Table 5** Sensitivity analysis under varying policy priorities.*

Scenario	Weighting Adjustment	Top Ranking	Stability
Base Case	Objective Entropy Weights	A4 > A3 > A5	–
Economic Priority	+20% Economic Weight (E1–E3)	A4 > A5 > A3	Stable
Environmental Priority	+20% Env. Weight (ENV1–ENV5)	A4 > A3 > A2	Highly Stable
Social Priority	+20% Social Weight (S1–S4)	A3 > A4 > A2	Moderate

Alternative A5 (100% reprocessing) generates the highest economic return, with an NPV of $1,043.5 M, it ranks third overall (Ci = 0.741). However, the scenario is penalized by marked increases in freshwater stress (70.4 Mm^3 over the project life) and community disturbance impacts (Supplementary Material). These additional environmental and social burdens offset the economic gains associated with maximum copper recovery. These results demonstrate that maximum production does not necessarily correspond to optimal sustainability performance within resource-constrained regional systems.

TSF safety factor (T2) and AMD reduction (ENV4) drive the restorative mining narrative by transforming potentially liquefiable impoundments into stabilized landforms aligned with GISTM. While safety factor improvements from 1.88 to 2.29 are substantial, the results indicate that geotechnical stabilization alone is insufficient to achieve overall sustainability. Alternative A4 demonstrates that optimal performance is achieved when safety improvements are balanced with responsible environmental management and acceptable community impacts.

Sensitivity Analysis

Structural sensitivity analysis confirms the robustness of the identified "sweet spot" across various policy scenarios (Table 5). Under an Economic Priority scenario, A5 improves its rank but fails to overtake A4, as extreme CAPEX and OPEX requirements act as a financial drag. Environmental Priority scenarios penalize A5 further due to its high carbon footprint and energy intensity. Shifting to a Social Priority favors Alternative A3 (60% reprocessing), highlighting the critical trade-off between job creation and local nuisance effects. Results suggest an optimal operating range between 60% and 80% reprocessing.

Adjusting economic weights (E1–E3) promotes A5 to second rank, as full-scale extraction maximizes production and NPV (Bascetin and Nieto 2007; Araya *et al.* 2020). Nevertheless, A4 remains optimal by avoiding the extreme capital and operational costs characterizing the 100% scenario. Elevating environmental weights to 50% penalizes A5 for high carbon and energy intensity (Marín *et al.* 2022; Adrianto *et al.* 2023), while moderate reprocessing (A2–A4) proves more resilient. Prioritizing social factors (S1–S4) favors A3 (60% reprocessing), highlighting critical trade-offs between employment and community disturbance. Medium-scale operations appear most sustainable for securing a Social License to Operate.

Conclusion

This study demonstrates that the sustainability of historical tailings reprocessing is characterized by a non-monotonic relationship between extraction intensity and overall performance. Entropy–TOPSIS analysis identifies 80% reprocessing (A4) as the sustainability efficiency peak. This optimal scenario maximizes the trade-off between restorative gains, such as copper recovery, acid mine drainage (AMD) load reduction, and geotechnical stabilization, and the constraints of regional water scarcity and social acceptance.

Analysis confirms that the "no-action" baseline is neither a neutral nor a sustainable option, as it perpetuates long-term environmental liabilities and economic loss. However, the study also identifies a clear sustainability ceiling; moving from 80% to 100% reprocessing triggers disproportionate penalties in water withdrawal, electricity demand, carbon footprint, and community disturbance that marginal economic gains cannot offset.

These findings suggest that "restorative mining" projects should be managed within a strategic operating envelope rather than pursuing maximum volume. By aligning mineral recovery with the Global Industry Standard on Tailings Management (GISTM), operators can transform legacy risks into stabilized landforms while maintaining their Social License to Operate. While the results are site-specific to the Iberian Pyrite Belt, the TEES-based MCDM methodology provides a transparent, data-driven model for evaluating secondary resource projects worldwide, ensuring they contribute effectively to the green energy transition without shifting environmental burdens.

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Reference:

Adiansyah JS, Rosano M, Vink S, Keir G (2015) A framework for a sustainable approach to mine tailings management: disposal strategies. J Clean Prod 108:1050–1062. https://doi.org/10.1016/j.jclepro.2015.07.139

Adibi N, Ataee-pour M, Rahmanpour M (2015) Integration of sustainable development concepts in open pit mine design. J Clean Prod 108:1037–1049. https://doi.org/10.1016/j.jclepro.2015.07.150

Adrianto LR, Ciacci L, Pfister S, Hellweg S (2023) Toward sustainable reprocessing and valorization of sulfidic copper tailings: Scenarios and prospective LCA. Sci Total Environ 871:162038. https://doi.org/10.1016/j.scitotenv.2023.162038

Araya N, Kraslawski A, Cisternas LA (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

Araya N, Ramírez Y, Kraslawski A, Cisternas LA (2021) Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis. J Environ Manage 284:112060. https://doi.org/10.1016/j.jenvman.2021.112060

Atalaya Mining Plc (2023) Sustainability Report 2022. Atalaya Mining Plc

Atalaya Mining Plc (2024) Sustainability Report 2023. Atalaya Mining Plc

Atalaya Mining Plc (2025) Sustainability Report 2024. Atalaya Mining Plc

Bascetin A, Nieto A (2007) Determination of optimal cut-off grade policy to optimize NPV using a new approach with optimization factor. 107:

Bascompta M, Yousefian M, Vintró C, *et al* (2025) Sustainability Assessment in Mining: A CSR-Based Analysis Model for Social and Environmental Impact. Fudan J Humanit Soc Sci 18:329–345. https://doi.org/10.1007/s40647-024-00419-y

Blannin R, Frenzel M, Tolosana-Delgado R, *et al* (2023) 3D geostatistical modelling of a tailings storage facility: Resource potential and environmental implications. Ore Geol Rev 154:105337. https://doi.org/10.1016/j.oregeorev.2023.105337

European Commission (2023) Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials (Critical Raw Materials Act)

Figueiredo J, Vila MC, Fiúza A, *et al* (2019) A Holistic Approach in Re-Mining Old Tailings Deposits for the Supply of Critical-Metals: A Portuguese Case Study. Minerals 9:638. https://doi.org/10.3390/min9100638

Global Tailings Review (2020) Global Industry Standard on Tailings Management. International Council on Mining and Metals (ICMM); United Nations Environment Programme (UNEP); Principles for Responsible Investment (PRI), Geneva, Switzerland

Jiang F, Wu H, Liu Y, *et al* (2020) Comprehensive evaluation system for stability of multiple dams in a uranium tailings reservoir: based on the TOPSIS model and bow tie model. R Soc Open Sci 7:191566. https://doi.org/10.1098/rsos.191566

Johansson L, Bahrami A, Wallhagen M, Cehlin M (2024) A comprehensive review on properties of tailings-based low-carbon concrete: Mechanical, environmental, and toxicological performances. Dev Built Environ 18:100428. https://doi.org/10.1016/j.dibe.2024.100428

Kaneesamkandi Z, Rehman AU, Usmani YS, Umer U (2020) Methodology for Assessment of Alternative Waste Treatment Strategies Using Entropy Weights. Sustainability 12:6689. https://doi.org/10.3390/su12166689

Kursunoglu S (2025) A Review on the Recovery of Critical Metals from Mine and Mineral Processing Tailings: Recent Advances. J Sustain Metall 11:2023–2050. https://doi.org/10.1007/s40831-025-01126-y

Marín OA, Kraslawski A, Cisternas LA (2022) Estimating processing cost for the recovery of valuable elements from mine tailings using dimensional analysis. Miner Eng 184:107629. https://doi.org/10.1016/j.mineng.2022.107629

Noble A (2022) Technical Report On the Riotinto Copper Project

Noble, Bouza B, Pickarts (2018) Technical Report on the Riotinto Copper Project. Ore Reserves Engineering (prepared for Atalaya Mining Plc), Highlands Ranch, CO

Ramírez Rodríguez G (2023) Preliminary Economic Assessment Proyecto Riotinto | Riotinto District Huelva Province, Spain

Rosario-Beltré AJ, Sánchez-España J, Rodríguez-Gómez V, *et al* (2023) Critical Raw Materials recovery potential from Spanish mine wastes: A national-scale preliminary assessment. J Clean Prod 407:137163. https://doi.org/10.1016/j.jclepro.2023.137163