FROM LIABILITY TO ASSET: A SUSTAINABLE APPROACH FOR MINE TAILINGS REMEDIATION IN PERU

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ABSTRACT

The management of Mining Environmental Liabilities (MEL) presents a critical challenge for the sustainability of the Peruvian mining industry. While the remediation of these deposits has traditionally been treated as a sunk cost, advances in mineral processing now enable legacy tailings reprocessing to function not only as a self-funded remediation mechanism but also as a source of economic profit. This paper presents a framework for evaluating the viability of such projects throughout their lifecycle: from initial liability characterization to the design and closure of the new storage facility. It analyzes how project viability hinges on the convergence of technical, economic, environmental, social, and regulatory factors. The study emphasizes the engineering challenges determining safe execution, detailing the complexities of tailings extraction, handling, and final disposal. It highlights the necessity for rigorous analysis to mitigate geotechnical and geochemical risks. Finally, key sources of uncertainty are identified, and avenues for future research are proposed. The paper concludes that a thorough understanding of engineering challenges is fundamental to transforming the theoretical potential of these projects into a viable reality that contributes to a circular economy.

KEYWORDS

Sustainability, Reprocessing, Remediation, Liability, Asset, Circular Economy.

1. INTRODUCTION

Sustainable closure of environmental liabilities is a primary challenge facing the global mining industry in the 21st century. Tailings deposits, traditionally regarded as inert waste, pose significant environmental and social risks due to their volume, location, and potential to generate contaminants. However, advancements in processing technologies and the evolution of mineral economics have created an opportunity to transform these liabilities into assets through reprocessing. This strategy enables the recovery of valuable resources while reducing environmental risks, enhancing physical and chemical stability, and facilitating definitive site closure.

This paper explores the context, challenges, and opportunities of tailings reprocessing in Peru. It presents a conceptual framework and engineering proposals to foster the adoption of reprocessing as a pillar of the circular mining economy.

2. THE PERUVIAN CONTEXT: A LEGACY OF CHALLENGES AND OPPORTUNITIES

2.1 The Scale of the Challenge: Tailings and Liabilities in Peru

The accumulated volume of mine tailings worldwide exceeds 220 billion tonnes, with exponential growth driven by declining head grades (ICMM, 2021). In Peru, the mining industry generates approximately 100–150 million tonnes of new tailings annually. While no unified public registry of the total accumulated volume exists, historical tailings deposited from the 19th century to the present are estimated to be in the hundreds of millions of tonnes.

To manage this legacy, Peru developed the Mining Environmental Liabilities (MEL) inventory. Maintained by the Ministry of Energy and Mines (MINEM), this registry identifies and prioritizes abandoned sites posing risks to public health and the environment. As of the latest update, the inventory includes more than 6,000 identified liabilities—ranging from tailings deposits and waste rock dumps to open pits—concentrated primarily in the Andean region.

While this inventory facilitates regulatory oversight and risk prioritization for remediation, it currently lacks the detailed mineralogical characterization required to assess economic potential. Consequently, the vast majority of these legacy sites are viewed solely as environmental burdens rather than potential assets for a circular economy.

2.2 The Regulatory Landscape: Gaps and Opportunities

Peru's regulatory framework for MEL is primarily structured around the General Law of Environmental Liabilities of Mining Activities (Law No. 28271) and its implementing regulations, complemented by mine closure regulations (Law No. 28090) and relevant decrees issued by the Ministry of Energy and Mines (MINEM). These laws impose obligations on mining operators to identify, register, remediate, and closure of legacy sites, and provide guidelines for public and private participation.

While the existing framework provides a solid foundation for managing environmental risks associated with abandoned sites, several gaps remain regarding the reprocessing and valorization of legacy tailings. Notably, current regulations focus primarily on remediation and containment rather than resource recovery or circular-economy initiatives. There are no specific procedures and incentives for operators seeking to reprocess tailings, and regulatory pathways for obtaining permits are lengthy and complex, involving multiple agencies and levels of government.

Furthermore, the absence of a differentiated regulatory approach for innovative projects can disincentivize investment and technological development. Issues related to land tenure, environmental impact assessments, community consultation, and ongoing monitoring require clearer and more streamlined provisions to facilitate responsible project execution.

Nevertheless, these challenges present distinct opportunities. Updating and adapting the regulatory framework to explicitly support the sustainable reprocessing of legacy tailings could accelerate environmental remediation, promote investment, and foster innovation. Dedicated guidelines, incentives, fast-track permitting mechanisms, and improved inter-agency coordination would help close identified gaps and enhance the positive environmental, social, and economic outcomes associated with MEL management.

2.3 The Rationale for Reprocessing: Latent Mineral Value

Several factors explain why historical tailings often contain significant quantities of recoverable valuable minerals:

- **Limited technology at the time of operation:** Rudimentary processes and inefficient recovery methods often left target minerals in the tailings.
- **High cut-off grades:** Historically, only high-grade mineralization was economically viable to extract; low-grade material was often discarded.
- **Limited geometallurgical knowledge:** A partial understanding of mineralogical behavior often resulted in the loss of secondary or encapsulated metals.
- **Changes in mineral value:** Metals with limited market value in the past may now be considered strategic or valuable resources.
- **Separation and grinding limitations:** Concentration technologies did not adequately recover minor minerals, increasing the residual recoverable value in tailings.

These historical conditions turn many legacy deposits into potential sources of new revenue and opportunities to mitigate liabilities.

3. A FRAMEWORK FOR PROJECT VIABILITY: FROM CONCEPT TO EXECUTION

3.1 The Value Proposition: From Sunk Cost to Potential Asset

Traditionally, legacy tailings have been regarded as sunk costs—waste deposits representing only environmental liabilities and ongoing monitoring expenses. In Peru, these sites are often associated with risks such as water contamination, acid mine drainage (AMD), and physical instability. Consequently, they are frequently sources of social conflict and perceived as lasting impediments to land use.

However, advancements in mineral processing, stricter environmental regulations, and shifting commodity prices are altering this paradigm. Legacy tailings are increasingly viewed as potential assets capable of generating economic value to fund their own remediation. Reprocessing enables the recovery of minerals previously deemed uneconomic or technically unrecoverable, creating a revenue stream while reducing the volume and toxicity of the remaining waste. This approach shifts operations from a linear “take-make-dispose” model to a circular mining framework, maximizing resource efficiency and enhancing the social license to operate.

3.2 The Engineering Lifecycle: From Liability to Stable Landform

The transformation of a legacy tailings deposit from an environmental liability into a viable asset is a complex engineering endeavor. This journey, as visually summarized in Figure 1, is underpinned by a rigorous conceptual and engineering framework that guides the project throughout its lifecycle. The figure illustrates the critical transition from a high-risk liability to a dual-value outcome: a saleable economic asset and a stable, low-risk environmental landform.

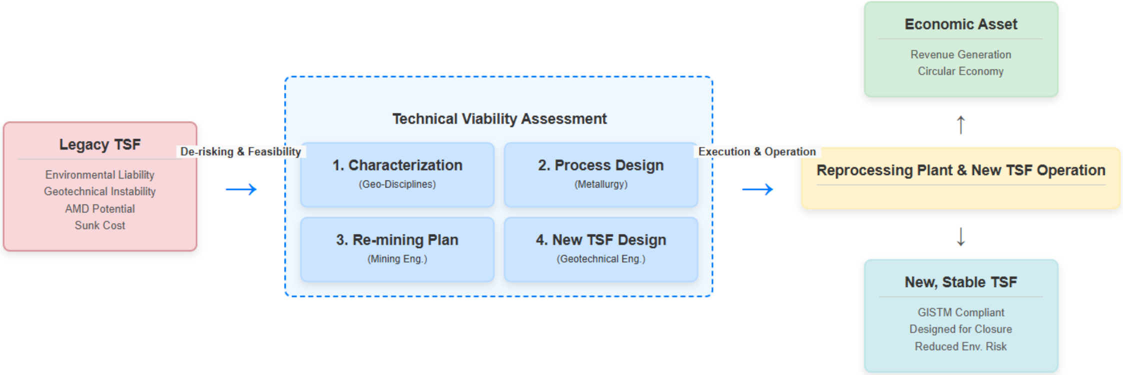

Figure 1 – The Lifecycle of a Tailings Reprocessing Project

3.3 Critical Factors for Technical Viability

3.3.1 Comprehensive Liability Characterization

The initial phase is critical, as all subsequent design decisions depend on a precise understanding of the material. Unlike primary ore bodies, tailings are engineered deposits with unique structural and chemical characteristics. The following should be considered for an adequate Liability Characterization:

- **Resource Estimation:** To attract investment, legacy tailings must be quantified as a mineral resource using systematic sampling and modern estimation techniques to develop a formal block model.
- **Geotechnical Assessment:** A rigorous investigation is paramount to assess the physical stability of the existing Tailings Storage Facility (TSF), particularly for older upstream dams susceptible to

static or seismic liquefaction. The program must include extensive in-situ testing—specifically Seismic Cone Penetration Testing (SCPTu) and testing in boreholes and test pits—alongside a laboratory testing program to characterize material properties. Stratigraphic sectioning is essential to identify distinct zones (e.g., silty sands vs. clays), as these variations directly dictate safe extraction methods.
- **Mineralogical & Geochemical Characterization:** Detailed sampling is required to create a spatial model of grade distribution. This must quantify not only valuable minerals but also deleterious elements (e.g., arsenic, mercury) which may increase treatment costs.

3.3.2 Processing Technology Selection and Optimization

The project's economic success depends on selecting a flowsheet that efficiently and cost-effectively recovers the target minerals. This requires extensive laboratory and pilot-scale metallurgical test work to evaluate technologies—such as flotation, gravity separation, or hydrometallurgical processes—and define a recovery strategy tailored to the specific mineralogy of the tailings. A sustainable design must also incorporate a comprehensive water balance model prioritizing closed-loop circuits to minimize freshwater intake. An effective plan for treating process effluents is equally essential to prevent secondary contamination and ensure environmental compliance.

3.3.3 Extraction and Transportation Engineering

The extraction process of tailings presents unique engineering challenges demanding a safe, efficient, and environmentally sound solution. The selection of the mining method, whether High-pressure Water Sluicing or mechanical excavation, is fundamentally dictated by the spatial distribution and stratigraphy of the target minerals within the impoundment, rather than solely by geotechnical constraints.

For deposits exhibiting homogeneous mineralization, High-pressure Water Sluicing offers a cost-effective bulk mining solution. However, in facilities where value is concentrated in erratic or lenticular layers selective mechanical excavation is required to minimize dilution and maximize recovery efficiency. This decision is inextricably linked to the design of an efficient material transport system, such as slurry pumping or overland conveying, which must be optimized to control operational costs and minimize the project's energy footprint.

3.3.4 Design of the New Tailings Storage Facility

A core principle of sustainable reprocessing is that the new facility designed to store post-process tailings must not become a future liability. Its design and operation must adhere to the highest international standards, such as the Global Industry Standard on Tailings Management (GISTM). The ultimate goal is to create a geotechnically and geochemically stable landform that require minimal long-term maintenance. This is often achieved by employing dewatering technologies—such as thickened, paste, or filtered tailings—which significantly enhance physical stability and reduce the environmental footprint. To this end, the closure plan must be an integral part of the initial design rather than an afterthought.

3.4 Management of Risks and Secondary Liabilities

While the primary objective is remediation, the reprocessing operation itself introduces specific risks. Failure to proactively manage these challenges can create "secondary liabilities," undermining environmental and economic goals. The three critical risk vectors are:

- Geotechnical Instability: Mining legacy tailings deposits, particularly those constructed using upstream methods, carries an inherent risk of triggering static liquefaction or slope failure during excavation. Rigorous sequencing is mandatory to maintain the stability of the remaining structure.
- Contaminant Mobilization: The disturbance of tailings exposes sulfidic minerals to oxygen and water, potentially accelerating Acid Mine Drainage (AMD) generation and heavy metal leaching.

Furthermore, post-process tailings constitute a new, often finer, waste stream that requires distinct geochemical characterization for safe disposal.

- Technical and Economic Volatility: Legacy tailings exhibit significant spatial heterogeneity in grade and mineralogy. This variability complicates plant optimization and can lead to fluctuations in recovery, making project profitability highly sensitive to robust sampling and metallurgical piloting.

3.5 Social and Investment Dimensions

A technically sound engineering plan is necessary but insufficient to guarantee success. True viability is achieved only when the project is embraced as a net positive by its key stakeholders and structured as a compelling investment. These dimensions are deeply intertwined and must be integrated into the project's strategy from its earliest stages.

The social license to operate (LSO) is arguably the most critical non-technical factor, particularly in a country with a complex mining history like Peru. Gaining social acceptance requires moving from consultation to active partnership. This involves transparent communication, participatory monitoring, and ensuring the project delivers tangible local benefits, such as direct employment and the visible, permanent remediation of a historical environmental liability.

To effectively manage this landscape, a strategic stakeholder analysis is essential. Figure 2 presents a typical Power/Interest grid applicable to Peruvian reprocessing projects. While site-specific analysis is mandatory, this framework generally categorizes "Key Players" (Regulators, Communities) as those requiring active collaboration, whereas "Investors" require a de-risked business case to maintain confidence. Proactive engagement with "Influential Observers" (NGOs, Academia) is equally critical to shape public perception.

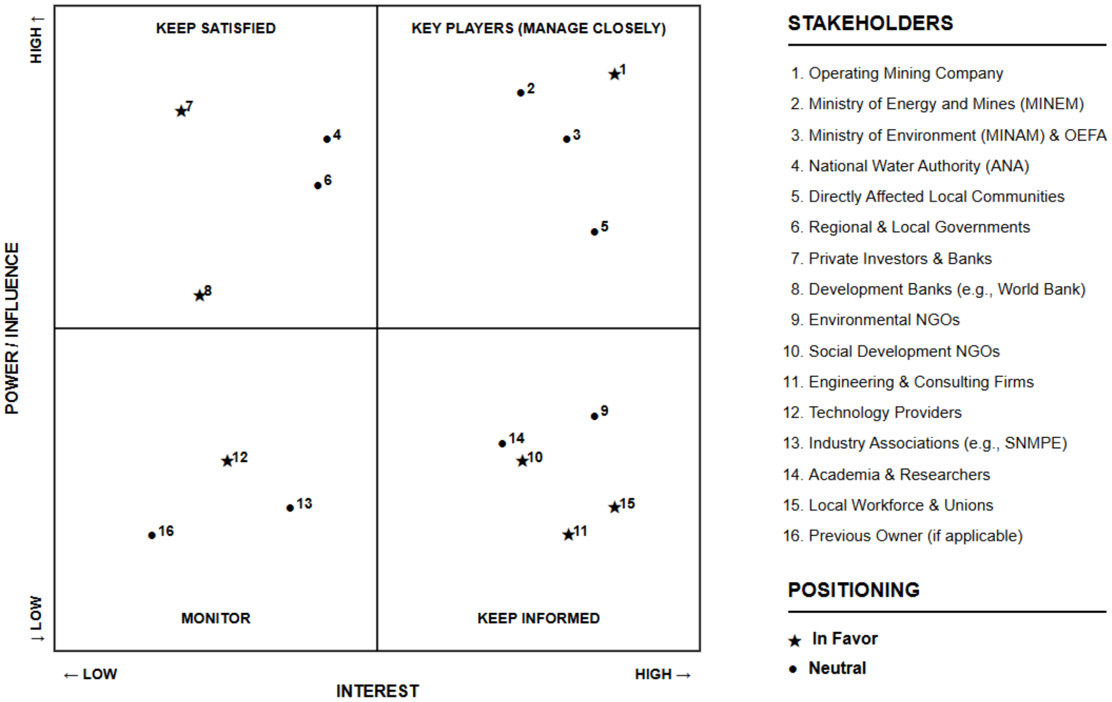

Figure 2 – Stakeholder Positioning Map illustrating the relationship between power/influence and interest for the identified stakeholders

Ultimately, a successful investment model leverages synergies between these stakeholders. The financial evaluation must quantify not only revenue from recovered minerals but also the critical value of eliminating the catastrophic failure risk associated with legacy facilities constructed under high geotechnical limitations. By removing these physical hazards, the project safeguards not only the asset owner but the reputation of the entire mining industry. This dual value stream, economic profit and verified safety, aligns the interests of investors, regulators, and communities, transforming the project into a robust investment for a circular mining economy.

4. DISCUSSION: AVENUES FOR FUTURE RESEARCH AND SOURCES OF UNCERTAINTY

4.1 Practical Insights: Key Lessons Learned

The application of the viability framework described in Section 3 has yielded several critical insights from direct consulting experience. These key lessons, which are essential for de-risking projects in practice, are summarized in Table 1.

Table 1 – Key Lessons Learned in the Design of Tailings Reprocessing Projects (Consulting Experience)

Common Challenge	Mitigation Strategy
Resource Characterization	
Underestimation of spatial and mineralogical variability.	A robust 3D block model is essential. Invest in a drilling campaign with a denser grid than standard for a TSF, supplemented by geophysical surveys to interpolate between points.
Over-reliance on historical plant data.	Historical data is a guide, not ground truth. Post-depositional oxidation and segregation alter mineralogy. Characterization must include detailed mineralogical analyses (e.g., QEMSCAN) to define actual recoverability.
Geotechnical & Execution Risks	
Instability risk of the legacy dam tailings mining process.	Hydraulic mining, while cost-effective, can induce instability. A detailed stability analysis is mandatory. Sequenced mechanical excavation, based on a rigorous mining plan, is often the safer option for sensitive deposits (e.g., upstream construction).
Designing the new TSF as a mere waste container.	The new TSF must be designed for closure from Day 1. Using filtered or paste tailings technology, despite higher CAPEX, drastically reduces long-term risk, maximizes water recovery, and facilitates progressive rehabilitation.
Geochemical & Environmental Risks	
Acid generating potential of the new (post-process) tailings.	Post-process tailings have a different geochemical reactivity. Characterization must include kinetic tests (e.g., humidity cells) on the new material to predict long-term acid generation and design the appropriate closure cover system.
Social & Regulatory Viability	
Community perception of the project as "new, polluting mining".	The narrative framework is critical. From Day 1, the project must be framed and managed as an environmental remediation and land sanitation initiative that also generates economic value. Participatory environmental monitoring committees should be established to build trust.

4.2 Navigating Uncertainty: An Integrated Engineering Approach

The transformation of a legacy liability into a productive asset is not a singular event but a process of systematically reducing uncertainty. Experience dictates that skipping assessment stages to accelerate production—a common temptation when commodity prices are high—invariably leads to project failure or the creation of secondary liabilities.

To navigate the unique uncertainties of tailings reprocessing, a rigorous "Stage-Gate" execution model is required. This approach, standard in major capital projects, must be adapted to the specific nuances of anthropogenic deposits:

- Scoping Level (Conceptual): The focus is on "fatal flaw" analysis. At this stage, uncertainty is highest (often ±35-50%). The engineering team relies on historical records and limited surface sampling to validate the basic business case. The critical question is not "how much money will we make?" but "is there a viable resource and a safe disposal solution?"
- Pre-Feasibility (PFS): This stage marks the transition from historical data to site-specific data. It requires a preliminary drilling campaign to define the resource and geotechnical stability. Metallurgical testing moves from the beaker to the bench scale. The goal is to select the single best development case, reducing uncertainty to a range of ±20-30%.
- Feasibility (FS): To support a Final Investment Decision (FID), uncertainty must be minimized to ±10-15%. For tailings, this necessitates a representative bulk sampling program and, crucially, pilot-scale processing. Unlike a mine, where the ore body is fixed, a tailings project allows for engineering the feed (e.g., blending). The pilot plant validates that the proposed flowsheet works on the actual variable feed, not just a composite sample.

To operationalize this structured process, we propose applying an "Integrated De-Risking Matrix." Table 2 presents a typical framework illustrating that engineering confidence must advance synchronously across all critical disciplines. While this matrix should be adapted to the site-specific context of each project, it provides a roadmap for conducting a comprehensive assessment, with uncertainty systematically reduced and risks mitigated across all engineering stages.

Table 2 – Integrated De-Risking Matrix for Tailings Reprocessing Projects

Discipline	Scoping (concept) (fatal flaw analysis)	Pre-feasibility (PFS) (option selection)	Feasibility (FS) *(Execution / FID)*
Resource (The Asset)	• Historical production records. • Topographic reconstruction. • Surface grab sampling. **Output**: Inferred Potential	• Wide-spaced drilling (e.g., Sonic on 100m grid). • In-situ density measurements. • Initial 3D Block Model. **Output:** Indicated Resource	• Tight-spaced drilling (e.g., Sonic on 25m grid). • Geostatistical Kriging (Short-range variability). • Reconciliation with pilot data. **Output:** Measured Resource
Geotechnics (The Stability)	• Visual site inspection. • Review of "As-Built" records. • Dam break inundation concept. **Output:** Hazard Classification	• In-situ testing (CPTu, Vane Shear). • Vibrating wire piezometers. • Phreatic surface control concept. • Limit Equilibrium Analysis. **Output:** Prelim. Factor of Safety	• Specialized lab testing program. • Seismic deformation modeling (2D/3D). • Liquefaction triggering analysis. • Active dewatering & drainage design. **Output:** Tailings mining criteria
Metallurgy (The Process)	• Literature review. • Theoretical mass balance. • Historical mill performance data. **Output:** Theoretical Recovery	• Bench-scale composites. • Mineralogical analysis • Variability testing (Oxide/Sulfide). **Output**: Prelim. Flowsheet	• Continuous Pilot Plant campaign. • Locked Cycle Tests. • Dewatering pilots (Paste/Filter). **Output:** Final Process Design
Water & Geochem (The constraint)	• Regional climate data review. • Static Acid Base Accounting (ABA). **Output:** Conceptual Water Balance	• Static site water balance. • Hydrogeological conceptual model. • Humidity Cells (Kinetic start). **Output:** Water Supply Strategy	• Probabilistic/Dynamic Water Balance. • 3D Groundwater flow modeling. • Solute transport modeling. **Output:** Effluent Management Plan
Social and Closure (The Leagacy)	• Land tenure verification. • Conceptual end-landform use. **Output:** Social Mapping	• Environmental baseline initiation. • Stakeholder engagement plan. • Trade-off: Wet vs. Dry Closure. **Output:** Social License Strategy	• EIA Submission & Social Agreements. • GISTM-compliant Closure Plan. • Post-closure monitoring design. **Output:** Final Investment Decision (FID)

4.3 Strategic Actions and Required Synergies

Addressing the key uncertainties identified requires a concerted effort from both public and private stakeholders. To move from a handful of isolated projects to a systematic national strategy, the following lines of action are proposed, grouped by the key stakeholders responsible for their implementation.

4.3.1 For Government and Regulators

- Develop a Differentiated Regulatory Framework: Create regulations recognizing reprocessing as a dual mining-remediation activity, aiming to shorten evaluation times and provide legal certainty.
- Establish an Inter-Institutional "One-Stop Shop": Organize an efficient and centralized management system to coordinate permits and approvals between ministries (MINEM, MINAM) and other relevant agencies (ANA, OEFA), reducing bureaucratic friction and accelerating project timelines.
- Implement Incentives and Promotion Policies: Implement fiscal incentives to attract private investment, rewarding the permanent closure of environmental liabilities.
- Create a National Geometallurgical Registry: Evolve the MEL inventory into a database with detailed geometallurgical data to allow pre-screening of deposits with high economic potential.

4.3.2 For the Mining Industry and Project Developers

- Lead Informed Social Participation: Move beyond consultation to develop partnership programs ensuring communities understand the risk-reduction benefits, fostering the trust required for a social license.
- Pilot New Technologies: Invest in innovative characterization and dewatering technologies adapted to Peruvian legacy tailings to bridge the gap between theoretical potential and reality.

4.3.3 For Academia and Research Institutions

- Investigate Remote Sensing for Characterization: Validate satellite-based hyperspectral imagery as a cost-effective tool for regional mineralogical screening.
- Advanced Geometallurgical Models: Develop models predicting metallurgical performance for complex, oxidized legacy tailings to reduce technical uncertainty.

4.3.4 Key Stakeholders and Potential Synergies

- Public-Private Partnerships: Governments and investors can mitigate financial risk by partnering to fund projects, integrating them into broader regional restoration efforts.
- Shared Infrastructure: In districts with clustered liabilities, companies can collaborate on shared processing and disposal facilities (co-disposal). This dramatically decreases CAPEX and improves operational efficiency.
- Technological Collaboration: Joint piloting between industry, technology providers, and academia accelerates the adoption of cleaner technologies, enhancing recovery rates and strengthening the local knowledge base.
- Strengthened Social License: Involving communities as active partners in planning and monitoring builds trust, transforming potential conflict into shared value through local employment and visible remediation.

4.4 The Next Frontier: Innovations in Processing and Disposal

Looking forward, the viability and scope of tailings reprocessing will be amplified by continuous innovation in three key areas:

- Processing: Innovations aim to unlock value from complex, low-grade materials. While flotation remains a core technology, selective leaching and In-Situ Recovery (ISR) offer the potential to mitigate physical tailings mining risks, provided that sophisticated hydrogeological control is maintained to prevent groundwater contamination.

- Disposal: The industry is shifting toward denser, stable landforms. Filtered tailings produce a stackable "earth-fill" material, maximizing water recovery—critical in the arid Andes—and facilitating progressive closure. Furthermore, co-disposal (blending tailings with waste rock) integrates waste streams into geochemically stable landforms designed for closure from the outset.
- Digital Integration: Machine learning applied to large geometallurgical datasets that optimize material blending for process stability. Simultaneously, drones equipped with LiDAR and hyperspectral sensors allow for efficient, frequent monitoring of the physical and chemical performance of the new infrastructure.

5. CONCLUSIONS

The reprocessing of legacy tailings represents a unique opportunity to fundamentally shift the paradigm of environmental liability management in Peruvian mining, transforming a sunk cost into a driver for a sustainable circular economy. However, viewing these projects merely as resource recovery operations is insufficient. Success hinges on their execution as holistic engineering endeavors, encompassing the meticulous de-risking of a historical liability, the efficient operation of a complex processing plant, and the design of a stable, permanent landform.

This study concludes that the value of reprocessing extends beyond economics to the fundamental preservation of the mining industry's global reputation. Many legacy deposits were designed, constructed, and operated under historical standards that are now considered deficient and unsafe. By physically removing these facilities and redepositing the material in modern, engineered structures, the industry effectively eliminates a latent risk of catastrophic failure. This proactive elimination of hazard is imperative, as the reputational fallout from a tailings failure is devastating to the entire sector. Thus, reprocessing serves as the ultimate mechanism to safeguard the social license to operate.

As demonstrated through the proposed viability framework, profitability and safety are not guaranteed outcomes but the result of systematic uncertainty reduction. This requires the integration of three critical engineering pillars: rigorous resource definition to account for spatial variability, advanced geotechnical assessment to ensure stability during the extraction process, and robust metallurgical piloting to validate recovery from oxidized feedstocks. The application of a stage-gate execution model, specifically the Integrated De-Risking Matrix, is essential to prevent the creation of secondary liabilities and ensure bankability.

Ultimately, while the technical challenges are significant, the primary barrier to widespread adoption remains strategic. Unlocking the value of Peru’s mining legacy requires a modernized regulatory framework that actively incentivizes remediation through reprocessing. By fostering collaboration among government, industry, and academia to mitigate these projects’ risk, Peru can transform the environmental burden of its past into a sustainable engine for its future.

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