ZIBELINE INTERNATIONAL™ PUBLISHING

Geological Behavior (GBR)

DOI: http://doi.org/10.26480/gbr.01.2026.06.16

ISSN: 2521-0890 (Print)
ISSN: 2521-0491 (Online)
CODEN: GBEEB6

CrossMark

RESEARCH ARTICLE

FROM MINING WASTE TO MARKET VALUE: TECHNOLOGICAL AND ECONOMIC FEASIBILITY OF TAILINGS-BASED CONSTRUCTIONS MATERIALS

Bello Aliyu[a*], Safirat Hashimu[b], Isah Shaibu[c], Eneojo Godwin Ameh[d], Khadija Muhammad Auwal[e]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, College of Earth Science, Chengdu University of Technology, Chengdu, China
[b] Department of Microbiology, Faculty of Sciences, Federal University Gusau, Zamfara State, Nigeria
[c] Department of Geology and Mining, University of Abuja, FCT Abuja, Nigeria
[d] Department of Geological Science, Faculty of Science, Federal University Gusau, Zamfara State, Nigeria
[e] Department of Geology, Faculty of Science, Bayero University, Kano, Kano, Nigeria
****Corresponding Author Email: belloncyaleeyu@gmail.com***

ARTICLE DETAILS

Article History:

Received 19 January 2026
Revised 25 January 2026
Accepted 18 February 2026
Available online 27 February 2026

ABSTRACT

Mine tailings and waste, a by-product of mineral extraction, represent both an environmental challenge and a potential resource for secondary mineral recovery and further use. In response to increasing global demand for critical raw materials and the drive toward sustainable mining practices, this study evaluates the economic and technological feasibility of tailings reprocessing. The research focuses on maximizing the recovery of residual minerals, repurposing tailings for industrial applications, and minimizing environmental impact. Key areas explored include the commercial viability of tailings utilization, cost-effective technological techniques, and a proposed processing scheme aimed at optimizing mineral recovery while reducing operational costs. Market analysis suggests strong demand for processed tailings in the production of whiteware ceramics, bricks, pipes, tiles and other materials essential for sustainable infrastructure. Hypothetical data indicate that approximately 70,000 tons of tailings could be repurposed annually, generating estimated cost savings of up to $5.5 million. These findings underscore the potential for transforming mine tailings from waste into a commercially viable and environmentally sustainable resource. The study contributes to ongoing discourse on responsible resource management and circular economy strategies in the mining sector.

KEYWORDS

Mine, waste, Tailings, Economics, Recovery, Environment, and Technology

1. INTRODUCTION

The world as a global community benefits from the whole processes of mining because it makes there end product accessible for the 21st century's technology, infrastructure, and energy demands. Amongst the end products, there are products that are not properly utilized, 'mine tailings'. Generally, mine tailings are disposed of in large impoundments or ponds near the mining site. Due to the fact that mining waste and tailings are typically dumped into lakes, rivers, or even the ocean is a significant source of concern in the mining industry. The environmental impact of these improper disposal is more evident now than ever, as they continue to accumulate, with estimates showing global generation of over 100 billion tonnes of waste rock and 10–15 billion tonnes of tailings annually (Azapagic, 2004; Lottermoser, 2011). These practice often result in acid mine drainage, heavy metal contamination, land and environmental degradation to the ecosystem and surrounding communities.

According to the study, mining waste utilization can benefit the host community/country's economy in a variety of ways boosting local economy and international trade while conserving the environment (Vitti and Arnold, 2022; Reconalla, and Eguia, 2024). However, due to advancements in mineral recovery technologies and the growing scarcity of high-grade ores, tailings have gathered attention as possible sources of valuable minerals and other industrial materials (Edraki et al., 2014). This would reduce the use of other natural building materials and eliminate the need for extensive land areas to store mine tailings, lowering the economic and environmental costs.

1.1 Background

Mining is an unavoidable anthropogenic process that occurs worldwide and frequently alters the land's shape and environment as a whole. More than 101 minerals are being produced yearly around the world from different mines, which includes but not limited to fuels, metallic, non-metallic, atomic and minor minerals. Mitigating the environmental and social impacts (water contamination, habitat destruction, and the release of potentially harmful substances) associated with their disposal is one of the main reasons for considering the utilizing of waste mine tailings. This study will reveal how mine tailings from sites could be further assessed and utilized for greater products while helping to eliminate and lessen the environmental impact and be economically sustainable. In the last few decades, mining activities has been globally increased tremendously to produce the required quantity to meet up with the technology, energy and infrastructure demands. In real sense, the annual amount of mine tailings generated by industries exceeds 10 billion tons (Adiansyah et al., 2015) and is expected to grow due to the increasing production forecast by 2035, the proportion of tailings will double (CESCO, 2019). Simultaneously, the problems faced by mining industries are also going to increasing with increased production rate.

Quick Response Code	Access this article online	
	Website: www.geologicalbehavior.com	**DOI:** 10.26480/gbr.01.2026.06.16

The efficiency of chemical and mechanical extraction processes is never 100% and it is neither possible to reclaim all reusable and expended processing chemicals and reagents. They may also contain many other valuable elements as has been shown in numerous studies (Khorasanipour and Jafari, 2017; Andersson et al., 2015). However, due to improvements in mineral recovery technologies and the growing scarcity of high-grade ores, tailings have gathered momentum as potential sources of raw materials. They will be valuable minerals and industrial materials in the present global circular economy (Edraki et al., 2015, Jeswiet, 2017).

1.2 Business idea

The future of recycling everything from side streams for reuse is high in an economical manner. Waste rocks are excavated to reach the ore and are not financially viable in a mine. The volume that needs to be removed depends on the geometry and the shape of the ore body, along with the mining method used (open pit/underground mine). Waste rock must be characterized to find out what it contains. In some cases, it may contain minerals harmful to the environment, such as sulphide minerals. In such cases, the waste rock must be handled properly, and mine site remediation must occur immediately after mining. As the ore is processed and the valuable minerals are separated, fine-grained mineral sand remains as waste, called tailings. Due to its low value and remote location, over 95 % of the tailings are usually disposed of in landfills. This study aims to propose a framework to assess the following:

- Possibilities to process tailings.
- Could there be any potential to use tailings?
- What could be the best options for selling?
- What would be the best option to process tailings for the best value for money?
- Which technological schemes do you propose?
- What would be the market potential of this material?

2. Methodology

This project adopts a literature review and analytical approach, integrating the available and existing case studies, peer-reviewed journal articles, a hypothetical data, and technical reports to assess the potential reuse of mine tailings and waste rock. The methodological framework consists of the following components:

- Data Collection: Secondary data were sourced from reputable mining journals, published case studies, and technical databases relevant to mine tailings reuse and processing. These sources were selected for their authority, relevance, and scientific rigor. Only materials published within the last 10 years were considered, except for foundational studies critical to understanding historical trends. The inclusion of diverse geographical regions (e.g., Africa, South America, Costa Rica and Australia) ensures a balanced global perspective. This include,
    - Peer-reviewed journals such as *Journal of Cleaner Production*, *Minerals Engineering*, and *Resources Policy.*
    - Published case studies and conference proceedings from institutions such as the International Council on Mining and Metals (ICMM) and the United Nations Environment Programme (UNEP).
    - Technical databases and industry reports, including those from the U.S. Geological Survey (USGS), World Bank mining reports, and environmental agencies.
    - Books and academic texts focused on mining waste management and mineral processing technologies
- Evaluation Criteria: The analysis is guided by key criteria, including the following below and they were adopted to suit the specific objectives of this study.
    - Economic Viability: Cost- benefit analysis of reprocessing tailings against using traditional raw materials.
    - Mineral Content: Chemical and physical properties of the tailings, with emphasis on silica, alumina, and residual metals.
    - Environmental Sustainability: Impact on reducing ecological degradation, tailings footprint, and potential to mitigate environmental hazards.
    - Market Demand: Industrial relevance and demand for potential products such as ceramic tiles, construction materials, and pipes.
- Technology Assessment: Various processing techniques are evaluated and assed using key performance indicators such as scalability, cost effectiveness, recovery efficiency. They were analysed to determine the most appropriate technologies for different types of tailings.
    - **Cost-effectiveness** (operational and capital expenses)
    - **Scalability** (applicability to both large and small-scale mining operations).
    - **Recovery Efficiency** (percentage of recoverable valuable minerals from tailings).
- Hypothetical Case scenario: To be able to illustrate the real time practical scenario of potential tailing reuse, a hypothetical scenario was constructed. It assumes tailings generated from.
    - A gold mining operation.
    - A feldspar and Kaolin processing plant

In both cases, the tailings are presumed to contain high concentrations of silica and alumina which are critical for ceramic and tile production. These assumptions are based on average geochemical profiles reported in relevant literatures reviewed. These tailings are hypothesized to hold significant potential for reuse in industrial applications.

- Reliability of Secondary Data: All secondary data used in this study were cross- referenced and validated through multiple sources to ensure reliability. Where possible, datasets were selected from institutions known for their methodological transparency and adherence to quality control and research standards (e.g., Elsevier peer-reviewed publications and recognized industry bodies). The hypothetical scenario was built using averaged values from at least three independent studies to reduce the risk of data skew or bias.
- Suitability Justification: High levels of silica and alumina are ideal for ceramic, tile, and pipe applications, which require chemical stability, thermal resistance, and formability.
- Limitations:
- All estimates are based on theoretical yields and generalized market data.
- Environmental permitting and regulatory approvals are not factored into cost models.
- Real-world application may vary due to site-specific geochemical variability and infrastructure availability.

A revised technological model developed (Figure 1a, 1b) is referenced by (Tebago and Thandiwa, 2021). This model presents a flow chart for optimizing gold mine tailings management through beneficiation. The model aligns well with the aims of this project thereby illustrating how improved processing can enhancing both resource recovery and environmental sustainability.

For the purpose of this review and further analysis, Table 5 presents assumed geochemical composition data from a mine site. The results indicate a high content of silica and alumina, essential components for ceramic and tile production, supporting the economic feasibility of tailings reuse.

Mine Tailings

↓

Pre-treatment (Screening, Drying)

↓

Geochemical Characterization

↓

Beneficiation Process (Flotation, Gravity Separation)

↓

Material Segregation

↓ ↓ ↓

Silica | Alumina | Trace Metals

↓ ↓ ↓

Ceramic Use Applications | Refractory Materials | Recovery/Sale

Figure 1a: A Revised technological model for tailings reprocessing focused on resource recovery and sustainability (Adapted from Tebago and Thandiwa, 2021)

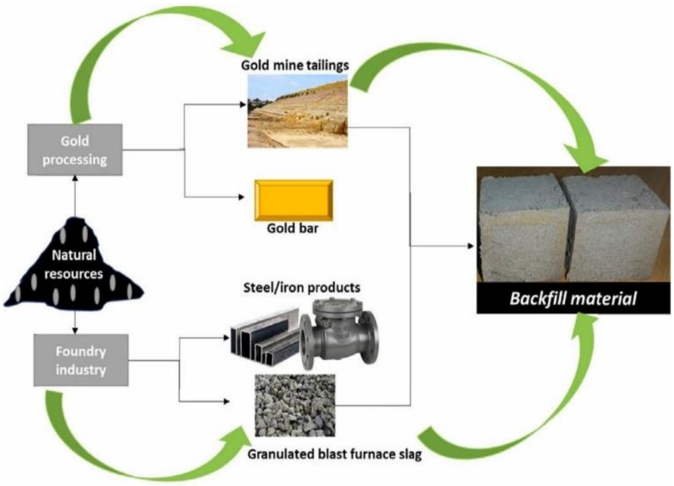

Figure 1b: Rethinking flow chart model for Gold mine tailing through Bencification adopted from (Tebago and Thandiwe, 2021).

2.1 Hypothetical Estimated Volumes and Economic Assessment

In this section, hypothetical assessment of the potential reuse of mine tailings in the production of ceramic whitewares, pipes, and tiles. The estimates below are based on assumed annual tailings generation from a medium-sized gold-copper or feldspar-kaolin mine.

2.1.1 Tailings Volume and Recovery Assumptions

- Annual Tailings Volume: Estimated at 1.5 million tonnes/year, based on average discharge rates from mid-scale mining operations.
- Recovery Volume: 1.2 million tonnes/year, assuming an 80% operational efficiency in collection and processing.
- **Workable Portion for Construction**: Assumed to be **900,000 tonnes/year**, factoring in losses due to impurities, fines unsuitable for processing, and moisture content.

2.1.2 Assumptions Made

- The tailings are non-hazardous and geochemically stable.
- Geochemical composition (see Table 5) supports suitability for industrial use.
- 75% of recovered tailings are usable for construction-related product development.

2.1.3 Recovery Rates for End Products

The recovery rates of valuable materials from tailings can vary based different processing methods used. For this model, the following products-specific recovery rates are assumed. These are based on benchmarks from pilot-scale studies (Francisco et al., 2021) and adjusted to reflect hypothetical yield conditions in a developing-country context.

i. Ceramic whitewares: 70%

ii. Pipes: 65%

iii. Tiles: 75%

2.1.4 Cost analysis

The total cost associated with utilizing tailings include, processing cost, transport costs, production cost, labour cost**.** Below is a hypothetical cost estimation breakdown.

iv. Processing cost: $H30/ton

v. Transportation cost: $10/ton

vi. Production cost: $50/ton

vii. Total cost per ton= processing cost + transport cost + production ($90/ton)

2.1.5 Limitations and Uncertainties

i. Transportation costs are location-dependent and may vary with fuel prices and terrain.

ii. Processing costs assume access to existing beneficiation facilities and may vary.

iii. Labour costs are not regionally adjusted and may fluctuate with wage regulations across different countries

2.1.6 Market Price

i. Ceramics whitewares: $150/ton

ii. Pipes: $120/ton

iii. Tiles: $130/ton

2.1.7 Revenue and profit estimates calculation

a) ***Ceramic Whitewares***:

- Revenue = Volume * Price = 70,000 tons * $150/ton =

$10,500,000

- Cost = Volume * Cost per ton = 70,000 tons * $90/ton = $6,300,000
- Profit = Revenue - Cost = $10,500,000 - $6,300,000 = $4,200,000

b) ***Pipes***:

- Revenue = Volume * Price = 65,000 tons * $120/ton = $7,800,000
- Cost = Volume * Cost per ton = 65,000 tons * $90/ton = $5,850,000
- Profit = Revenue - Cost = $7,800,000 - $5,850,000 = $1,950,000

c) ***Tiles***:

- Revenue = Volume * Price = 75,000 tons * $130/ton = $9,750,000
- Cost = Volume * Cost per ton = 75,000 tons * $90/ton = $6,750,000
- Profit = Revenue - Cost = $9,750,000 - $6,750,000 = $3,000,000

***Summary of Financial Outcomes*:**

- Total Profit from Ceramic Whitewares: $4,200,000
- Total Profit from Pipes: $1,950,000
- Total Profit from Tiles: $3,000,000

ROI Calculation:-Net Profit / Capital Costs × 100

Utilizing tailings as a raw material for producing these materials (ceramic whitewares, pipes, and tiles) presents a possible opportunity to convert waste into valuable products figure 2. It illustrates a process model adapted from, showing the beneficiation flow and conversion of tailings into ceramic products, emphasizing the principles of circular economy and sustainable material reuse (Francisco et al., 2021). The model demonstrates a potential pathway for sustainable waste management and resource recovery in the mining industry. With a total estimated profit of approximately $9.15 million annually from the proposed operations, this approach may not only promote sustainable practices but will also boost an economic value to what would otherwise be considered waste.

Table 1: Assumed geochemical composition of mine tailings indicating high silica and alumina content suitable for ceramic and industrial applications.

Component	Percentage %
Silica SiO_2	58
Alumina Al_2O_3	21
Iron oxide Fe_2O	8
Feldspar	6
Kaolinite	11
Magnesium oxide MgO	2
Potassium Oxide K_2O	4
Sodium Oxide Na_2O	2

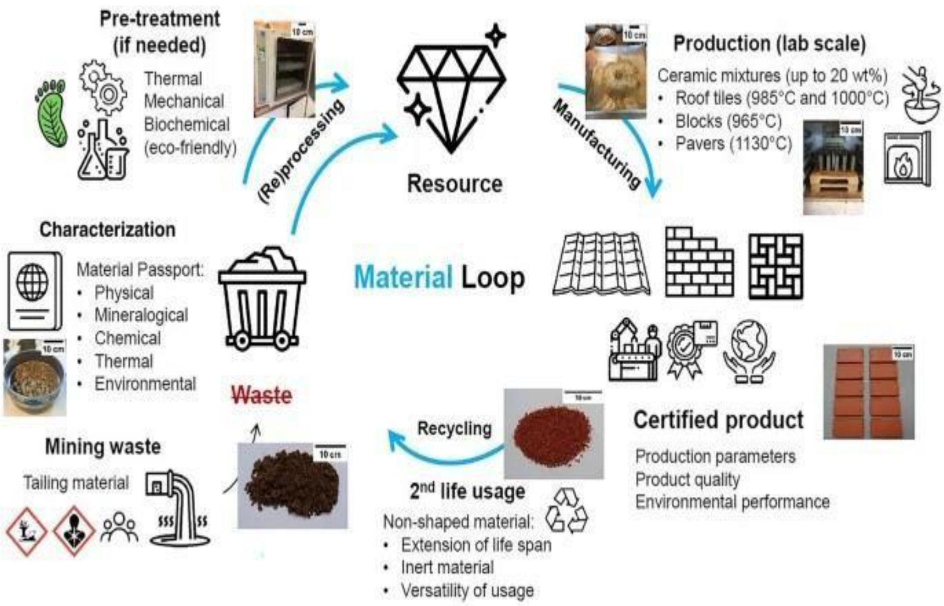

Figure 2: A practical model and approach for converting mine waste into a ceramic resources, adopted from (Francisco et al., 2021).

2.2 Hypothetical Product Development Using Tailing

This section explores potential industrial applications based on the assumed composition of tailings. The focus is on cost, performance, and feasibility.

2.2.1 Pipes from Tailings-Based Composites

Using silica-rich tailings combined with epoxy resin, pipes can be fabricated with improved abrasion resistance.

- **Yield**: 1 ton of pipes per 2.2 tons of tailings
- **Composition**: Silica-rich tailings + epoxy resin
- **Durability**: 20% higher wear resistance than HDPE
- **Cost**: $520/ton (vs $750/ton for commercial alternatives)
- **Assumption**: Sourcing local resins and optimizing compounding processes to minimize material cost

2.2.2 Tiles from Ceramic Tailings

Clay-rich tailings with feldspar and kaolinite are ideal for floor tiles after being moulded and kiln-fired.

Cite The Article: Bello Aliyu, Safirat Hashimu, Isah Shaibu, Eneojo Godwin Ameh, Khadija Muhammad Auwal (2026). From Mining Waste to Market Value: Technological and Economic Feasibility of Tailings-BasedConstructions Materials. Geological Behaviour 10(1): 06-16.

- **Yield**: 1 m^2 of tile per 8 kg of tailings
- **Composition**: Clay-rich tailings containing feldspar and kaolinite
- **Water Absorption**: <5% (meeting ISO ceramic tiles standards)
- **Cost**: \$2.20/m^2 (vs \$3.80/m^2 commercially)
- **Assumption**: Uniform particle size and appropriate kiln firing temperature achieved.

2.2.3 Road Construction Aggregates

Processed tailings replace sand and gravel in sub-base layers.

- **Use rate**: 1 km road = 1,500 tons of tailings
- **Strength**: California Bearing Ratio (CBR) = 80% (suitable for sub base applications)
- **Cost savings**: 25% lower per km compered to standards for compaction and load bearing capacity.
- **Assumption**: Tailings meet geotechnical standards for compaction and load-bearing capacity.

3. Discussion

The increasing volume of mine tailings generated annually presents not only a persistent environmental and geological challenge but also an underexplored economic opportunity. With the global shift towards sustainable development, the mining industry must evolve to meet environmental and resource efficiency standards. One idea is to leveraging mine tailings as a raw material in manufacturing and construction industry, reducing waste and potentially lowering costs compared to the traditional methods. Transforming tailings into secondary resources offers numerous socio-economic, geological, and environmental benefits. For instance, successful tailings repurposing projects in South Africa and Chile have demonstrated reduced reliance on virgin materials, cost savings, and decreased ecological impact and some studies in Namibia and Costa Rica (Tutu et al., 2020; Navarro et al., 2019; Harrison and others, 2002). This approach can contribute to a sustainable and circular economy with a potential to save time, cost, resource consumption in the mining, construction industry leading to environmental protection. It is quite important to develop cost-effective technology using these tailings can reduce environmental risks and benefit communities by eliminating the dangers of storing tailings on the surface (Yu et al., 2021).

As stipulated, bricks and other could be designed from these wastes, and can support buildings, facades, floors of civil works, sidewalks, parks, central squares, and even tracks and roads due to their excellent resistance by (Calderon et al., 2020). The reuse of mineral residues as aggregates to prepare concrete materials for road and bridge construction presents the state of development of mining community construction in a more friendly and competitive cost.

However, while these case studies show promising results, replicating such success at a global scale across different countries and regions faces several contextual challenges. As reported for instance, tailings from different regions often exhibit significant variability in mineralogical and geochemical composition, which can limit the standardization of reuse technologies by (Kossoff et al., 2014; Chen et al., 2023). Additionally, regions with weak environmental regulations or political instability especially across some African countries may find it difficult to attract the investments necessary for large-scale tailings reprocessing. Differences in infrastructure, logistics, and energy access further complicate implementations accordingly. For example, exporting and transporting tailings from remote mines to processing centres may be economically prohibitive unless on-site processing solutions are adopted. Therefore, broader implementation requires adaptable, decentralized technologies and flexible policy frameworks that consider local realities.

Another critical factor influencing tailings utilization is market volatility, particularly in metals pricing and construction material demand. For instance, during periods of low metal prices, the economic incentive to reprocess tailings for metal recovery diminishes sharply (Ghorbani et al., 2021). Similarly, the demand for construction materials such as bricks or ceramics may fluctuate based on regional housing booms, global supply chain disruptions, or inflationary pressures. These market dynamics necessitate robust financial modelling and risk mitigation strategies in any proposed tailings valorisation project. Situations like the 2023 slump in copper prices, for instance, delayed several reprocessing ventures in South America that were previously considered economically feasible (Ghorbani et al., 2021).

Additionally, changes in environmental and mining policies play a dual role—either enabling or restricting tailings reuse. Recent policy shifts, such as the EU's Green Deal and Canada's strengthened tailings management rules under the Metal and Diamond Mining Effluent Regulations in 2021, have encouraged industries to invest in circular economy practices (European Commission, 2022). On the other hand, in jurisdictions where mining codes are outdated or enforcement is weak (e.g. across Africa countries), tailings reprocessing may face bureaucratic bottlenecks or public resistance due to historical environmental harm. A lack of inter-ministerial coordination between mining, environment, and construction sectors also often leads to fragmented implementation.

3.1 Potential for Tailings Utilization

As shown in Figure 3 below, there are essential evaluation criteria for assessing the feasibility and effectiveness of intended tailings activities. These serve as a framework for informed decision making and sustainable management of tailing resources. Mine tailings waste can be utilized and developed into industrial products such as cement, whiteware ceramics, bricks, and tiles (Zhang et al., 2012). These procedures have been explored in India and China, Costa Rica where tailings have been successfully used in bricks and road base construction, thereby reducing raw material costs by about 30% (Singh et al., 2018). This approach not only reduces landfill volumes but also supports a circular green economy. Additional applications include underground backfilling and land reclamation strategies (You et al., 2020), with proven benefits in Australia where such practices have reduced surface footprint and enhanced mine site restorations (Lottermoser, 2010).

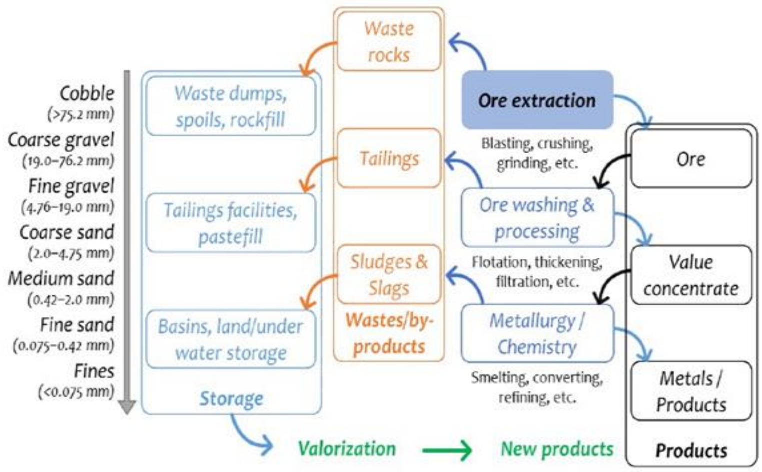

Figure 3: Key assessment criteria for intended Tailings and Waste revitalization activities

Mine waste revitalization arouse a lot of positive or negative various expectations. Therefore, each revitalization process would be carefully implemented figure 3 that includes, Specification of the properties on a very detailed level, identification of the current revitalization status, development of a number of revitalization alternatives for consideration, assessment of the alternatives with respect to risk reduction using financial, and non-financial criteria.

Furthermore, recent advancement in technological are helping to overcome the historical limitations of tailings reuse. For example, the development of mobile beneficiation units and AI-powered mineral sorting technologies enables site-specific processing and reduces capital investment risks (Zhou et al., 2022). The integration of life cycle assessment (LCA) tools also supports the selection of environmentally optimal processing routes. In Brazil, the recent application of microwave-assisted comminution has drastically reduced the energy cost of liberating valuable minerals from legacy tailings (Silva et al., 2023). These innovations are reshaping how mining companies evaluate the cost-benefit profile of reprocessing initiatives. Figure 4. A flowchart depicting the key stages of the mining cycle, starting from ore extraction through to metal and mineral beneficiation processes. Adapted from (Guyena et al., 2018).

3.2 Feasibility of Tailings Reprocessing

Many tailings contain significant residual minerals due to past inefficiencies in extraction. Reprocessing becomes feasible when the market prices of metals are usually high, the tailings are accessible and geochemically stable and when the countries environmental regulations support recovery projects (Johnson et al., 2017). Techniques such as flotation, gravity separation, bencification and hydrometallurgy have shown promising results in reprocessing efforts (Brierley and Brierley, 2013). Also, experts like have proposed microwave-assisted comminution and flotation technologies in improving metal recovery from tailings at lower energy costs (Zhou et al., 2022). Similarly, demonstrated how artificial intelligence (AI) algorithms can be applied to automate mineralogical sorting, increasing yield and reducing processing time (Wang et al., 2023). These innovations not only improve economic feasibility but also reduce the environmental footprint of tailings reprocessing. Even though due to some limitations in skilled labour availability, government policy incentives and proper infrastructure could slow adoption of such technologies in many remote areas and developing communities.

3.3 Evaluating the Practicality of Tailings Processing

Some practical and real-world challenges include variability in tailings composition and government stakeholder's regulatory hurdles, but advancements in modular and mobile processing units offer new opportunities (Kossoff et al., 2014). Processing is practical when supported by:

- Detailed geological and geochemical analysis of waste.
- Economic assessment and modelling of recovery costs and returns.
- Market study
- Environmental impact assessments.

3.4 Commercial Options for Tailings Disposal and Sales

Stipulating laws by the government and stakeholders in the manufacturing and construction industries will compel and synergize the industry to create circular economic opportunities (Hudson-Edwards, 2016). So also, tailings can be directly sold or transferred to industries requiring bulk material. For instance, construction companies may purchase tailings for use in road base or as aggregates. Additionally, tailings with specific mineralogical characteristics can be sold to metal recovery firms or even agriculture (as soil amendment, depending on composition). Establishing partnerships with industrial players will turn waste into a sellable commodity. Industries out look that may purchase tailings for use include:

- Road construction and civil works.
- Soil conditioning (when chemically safe).
- Aggregates in building materials.
- Ceramic and white wares company
- Roofing sheets and roofing tiles.
- Pipes and plumbing industries.

3.5 Geological Implications of Tailings Reuse

Geologically, tailings are finely milled residues with heterogeneous mineral compositions. Figure 4 illustrates the major stages of the mining cycle from ore extraction to mineral bencification adopted from (Guyena et al., 2018). It provides visual representation of the mining process highlighting sequential steps involved in extracting and processing minerals. Advances in beneficiation and flotation can extract residual economic minerals, particularly from legacy tailings (Brierley and Brierley, 2013). In comparison, according to a study, tailings waste from a South American copper mines have been shown to contain recoverable quantities of molybdenum and cobalt (Navarro et al., 2019). Chemical and mineralogical analysis is critical here, as it influences mechanical strength and chemical reactivity for construction purposes. For example, tailings high in quartz, Kaolin and feldspar are more suitable for white wares ceramic applications.

3.6 Environmental and Regulatory Considerations

Tailings that are not rehabilitated can result in acid mine drainage, heavy metal leaching, and sedimentation in water bodies. In Zambia alone, environmental degradation caused by mine tailings has led to extensive health issues in host and surrounding communities (Kangwa and Croucamp, 2008). Recycling mitigates these risks by stabilizing harmful components and reducing the spatial imprint of waste ion site. Strongly stipulated and adhered Government policies, such as that of Canada's Metal Mining Effluent Regulations (2021), support reprocessing through incentives and environmental safeguards. Regulatory compliance and environmental impact assessments are essential to ensure long-term sustainability.

3.7 Social Impact Assessment (SIA)

The processing of mine tailings, particularly from gold-copper and other feldspar-kaolin operations, presents several significant social implications. Tailings reprocessing not only reduces the long-term environmental burden on host communities near mine sites, but also creates job opportunities in material recovery, processing, and product manufacturing (e.g., tiles, whiteware ceramics, pipes, and construction aggregates etc.).

By reducing the environmental hazards associated with traditional tailings, disposal (such as dust emissions, water contamination, and land degradation) the project contributes to improved health and safety outcomes for surrounding populations even though there might be additional concerned issues to be raised. With careful implementation plan, these foreseen problems could be averted. The integration of beneficiation and reuse strategies also aligns with sustainable development goals, especially Goal 12 highlight (Responsible Consumption and Production) and Goal 9 (Industry, Innovation and Infrastructure).

Moreover, the adoption of such circular economy models can help foster positive relationships between mining companies and host communities, potentially improving the social license to operate.

3.8 Socio- Economic Implications

From a socio-economic perspective, tailings valorisation reduces waste management costs and introduces alternative revenue streams. Some key potential of socio-economic impacts of utilizing tailings and waste include; improved safety, employment opportunity, improved local economy, inward migration, averted storage expansion, road risk degradation etc. For instance, the excavation of the ponds storing the tailing waste, drying it, and transporting the material to industries or plants for use demand the input of labour. It will be expected that given the limited time scale of potential waste utilization project, it is anticipated that more than 5 skilled and unskilled people will be employed during the operation. There is also opportunity for transportation along the mine route, reduced noise and dust release within the immediate environment. In Brazil, reuse of bauxite tailings in ceramics has supported local SMEs and reduced unemployment (Da Silva et al., 2015). Similarly, in Ghana, artisanal brick-making from tailings has empowered local communities while reducing housing deficits. These outcomes suggest that with proper technical and market support, tailings-based industries can promote inclusive economic development. The production of building materials near mining sites also reduces transportation costs and enhances affordability.

From an operational perspective, community acceptance and stakeholder engagement are also essential. Projects that aim to reuse tailings for infrastructure must consider local environmental histories, community trust, and potential land use conflicts. Without inclusive stakeholder consultation, tailings reuse projects risk facing public opposition, especially in regions with past mining-related environmental disasters such as the recent occurrence in Brazil's Mariana and Brumadinho dam failures (Nazari et al., 2020). Thus, incorporating environmental justice principles into project planning is crucial for sustainable implementation.

3.9 Technological and Market feasibility

Technologies such as froth flotation, bioleaching, and beneficiation have been adopted in Sweden's LKAB project, which reclaimed iron from tailings with high efficiency (Gupta and Yan, 2020). Moreover, the global green construction market is projected to grow at a CAGR of 10.3% by 2030 (Allied Market Research, 2022), increasing demand for sustainable materials. Costa Rica's construction industry, despite its preference for reinforced concrete, presents a niche market for aesthetic, lightweight ceramics derived from silica-rich tailings.

However, tailings vary significantly in mineralogical composition based on ore type, local geology, and processing history, which affects their suitability for reuse. For example, while iron tailings may be suitable for concrete applications, copper tailings may contain higher levels of toxic elements such as arsenic or lead, requiring more rigorous treatment (Kossoff et al., 2014; Chen et al., 2023). In many African and South American countries, the lack of geochemical characterization and environmental baseline data further impedes efforts to standardize reuse protocols (Adiansyah et al., 2015). Moreover, smaller mining operations in developing regions may lack the capital or technical expertise to implement beneficiation and processing technologies that are often essential for making tailings usable in construction or ceramics (Silva et al., 2023).

3.10 Case Study 1. Waste Rock, Tailings, and Sludge as construction materials aggregate

Even though there is no existing present general mineral waste classification to ease the improvement of circular economy mining sustainability. There are 4 proposed categories of mineral waste as a source of construction and industrial material based on their potential usage in relation with their required degree of processing (Table 1) (Emery1978). It is highly suggested from the table classification that Type 1 minerals are largely useable in construction in the mining site as they represent large volumes with low industrial value with minimal processing.

Table 2: Classification of mineral wastes according to Mitchell 2004

Group	Description	Example	Potential End Uses
Type 1	Unprocessed wastes	Quarry Scalping, quarry blocks, colliery spoil	Fill, low grade road stone, armor stone, brick clay
Type 2	Processed waste- reclaimed mineral	Silica sand wastes, limestone wastes, building stone wastes	Silica sand , Kaolin, brick clay, mineral filler, aglime, aggregate
Type 3	Processed waste- added-Value Products	Lead/zinc wastes, pegmatite wastes, silica sand wastes	Fluorite, barite, feldspar, rare earth, mica, heavy minerals
Type 4	Beneficiated wastes	Certain wastes	Gemstones, high- value metals

3.11 Selection Guidelines Use of Road Construction Materials from mine waste and Tailings

In the year 1999, Transport Research Laboratory (UK) published guidelines for selecting road materials use. The guidance for the road materials selection as a base or subbase layer is presented in Figure 5 showing mining cycle from ore extraction to waste. It suggest appropriate solutions to designing requirements by evaluating the available options, identifying potential problems, and assessing necessary impacts. Recognition of parameters, e.g. material nature and properties, factors such as condition, environmental risks, project social impact, and economic constraints). In table 2 some of the required specifications are showcased. The 4 scenarios presented. The material is;

- Recommended; it meets all criteria for the targeted use and has an acceptable performance record in similar geotechnical and climatic environments. Its use should be promoted.
- Meets all criteria for the aimed use and has a satisfactory performance record but in significantly diverse geotechnical and climatic environments. An assessment of the impacts of the various conditions on the material must be conducted (i.e., traffic, climate, hydrology, and topography), with engineering context, construction method, and road maintenance program. Finally, special measures can be taken such as limiting its incorporation rates, or treatment with a hydraulic binder, or both.
- Meets selection criteria, but has not previously been used successfully, a review of potential problems identified by standard tests and criteria is required. Then, the material is to be considered as-is or after treatment.

If the material fails the selection criteria, for the targeted use after cross-checking that test methods are appropriate, review implications of environmental impacts and geotechnical characteristics are required. If modifying the material or the design will not lead to improved performance, it is recommended to downgrade it from the base to the subbase, or from filling to capping.

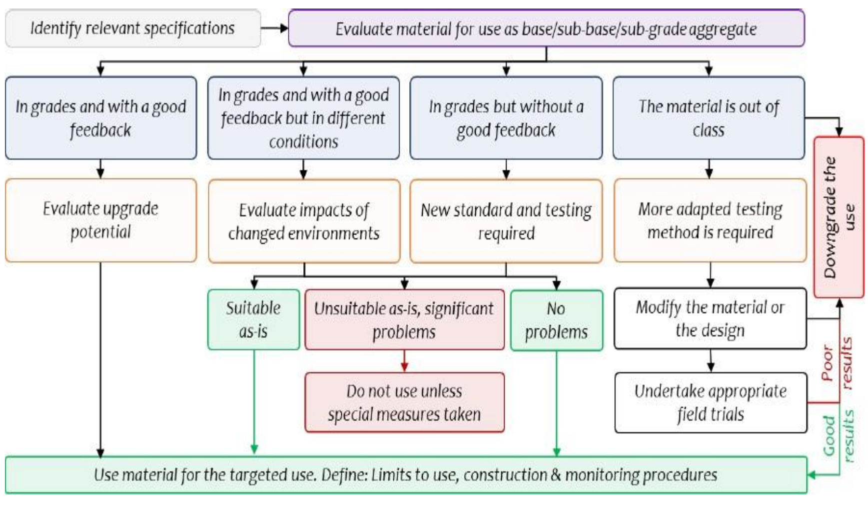

Figure 5. Aggregate selection assessment framework for use as a base or subbase material for road construction (after Guyena et al., 2018).

3.12 Case 2: Use of Waste and Tailings from a Silica Sand Quarry and processing Plant for ceramics, whitewares etc.

The waste from this site could be characterized and will possible show abundance in mixture of fine grained sand for glass making products and clay. Depending on the site and clay product, it could be fired during re processing to whites which will be suitable for whitware ceramics manufacture. However, if it fires to reddish brown colour, it will be suitable for brick manufacture or for production of pipes, tiles and some artisanal pottery especially where there is relatively small brick industries. The project financial appraisal for these will be based on the assumption that larger market could be developed locally and for international exports. Technical evaluation assessment will include waste sampling, waste evaluation (mineralogy, particle size distribution, chemistry).

Harrison and others 2002 made an assessment of bulk samples for use as whitwares ceramics and other structural ceramics e.g. bricks, tiles etc.

from Sicorsa silica sand Costa Rica. They assessed the mineralogy, particle-size distribution and chemistry. They reported that the waste sample assessed are dominated by quartz, with traces of mica, kaolinite and hematite as show in table 2. The samples are high in SiO2 ranging 91-97%. It also reflected high Al2O3 (27- 16%) Table 3. The particle-size distribution of the samples shows they are finer than 1mm. They reported that the samples are similar distribution to commercial brick clay. A financial and economic model proposed for the project is shown in table 3. The financial appraisal submits on the assumption that larger market for bricks within Costa Rica could be developed and the technology could be sold elsewhere across the globe. There will also an indirect market benefit as a result.

Table 3: Minerology of assessed Mines tailings from silica sand Quarry.

		F978	F799	F800	F801	G462	G463	G464	G466
Bulk Mineralogy	Dominant	Quartz	Quartz	Kaolinite	Quartz	Quartz	Quartz	Quartz	Quartz
	Major			Quartz					
	Minor	Kaolinite	Kaolinite		Kaolinite				
	Trace	Hematite?	Hematite	Hematite		Kaolinite	Kaolinite Boehmite?	Kaolinite	Mica (Muscovite?) Kaolinite? Hematite?
Clay Mineralogy	Dominant	Kaolinite	Kaolinite	Kaolinite	Kaolinite	Kaolinite	Kaolinite	Kaolinite	
	Major								Kaolinite
	Minor	Illite	Illite	Illite	Illite				Smecite Chlorite?
	Trace	Illite Smecite Smecite	Illite Smecite Smecite	Illite Smecite Smecite	Illite Smecite Smecite	Illite Smecite Smecite Chlorite	Illite Smecite Smecite Chlorite?	Illite Smecite Smecite Chlorite?	

Table 4: Chemistry of the Tailing Samples from the Mines

	%	F978	F799	F800	F801	G462	G463	G464	G466
MAJOR ELEMENT	SiO2	92.3	92.3	58.5	96.6	91.5	94.7	96.0	67.3
	TiO2	0.2	0.3	0.7	0.4	0.3	0.2	0.2	0.8
	Al2O3	4.0	4.4	26.6	4.7	2.7	1.9	1.6	16.3
	Fe2O3t	2.3	1.0	2.9	0.8	0.6	0.5	0.4	6.4
	Mn3O4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.1
	MgO	<0.05	0.1	0.2	0.1	<0.05	<0.05	<0.05	0.6
	CaO	0.1	0.0	0.1	0.0	<0.01	<0.01	<0.01	0.1
	Na2O	<0.05	0.1	0.1	0.1	<0.05	<0.05	<0.01	0.1
	K2O	0.2	0.4	1.1	0.4	0.2	0.2	0.2	1.7
	P2O5	0.0	0.0	0.1	0.0	<0.01	<0.01	<0.01	0.1
	SO3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Cr2O3	<0.01	<0.01	0.0	<0.01	<0.01	<0.01	<0.01	0.0
	SrO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.1
	ZrO2	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.0

Table 4 (cont): Chemistry of the Tailing Samples from the Mines

TRACE	BaO	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.1
	NiO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	CuO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	ZnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	PbO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	LOI	1.8	1.6	9.3	1.7	1.1	0.8	0.7	5.8
	Total	**100.8**	**100.1**	**99.4**	**99.7**	**99.6**	**99.6**	**99.7**	**99.4**

3.13 A Market Study for Waste as a raw material for bricks, tiles and pipes manufacturing.

Bricks, tiles and pipes are important building materials used worldwide. Although their considerable uses varies in different countries and civilisation depending on availability of clay, building style and design. They are made by shaping a plastic clay and calcining it in high temperatures. The clay is used either in its natural state or by blending clay and other non- plastic or poorly plastic materials from more than one source which helps in getting better control on quality and colour of final product. Blending of raw materials helps achieve greater control on the quality of the product swell as improving variety of colours and properties of the brick, tiles or pipes. The clay waste from the mine site may be considered a suitable raw material either for lending with a plastic clay or processed as a raw material in itself for bricks and tiles manufacturing.

Although, construction industry in Costa Rica is dominated by the use of mass concrete and concrete blocks, they also use steel reinforcement within structures to withstand earth quakes. Readily availability of cement also is a factor to consider.

3.14 Optimal Processing Techniques for Maximum Value

Best value-for-money outcomes and low-cost scalable methods are proposed to be used such as:

- Employ a Sensor-based sorting
- Heap leaching (for gold or copper samples etc.)
- Froth flotation (for sulphide ores): Enables separation of residual sulphides and recovery of fine particles, improving safety and consistency. It enhances efficiency and helps reduces sulphide content by 90% thereby giving an improved outcome of Safer and more stable material for tiles and roads
- Bioleaching (for low-grade tailings): This process utilizes microorganisms to remove impurities from tailings. By employing bio-bleaching techniques, we can enhance the whiteness and purity of the raw materials used in ceramics. This is particularly important for whitewares where aesthetic quality is paramount (Kumar et al., 2017).
- Bencification: Beneficiation involves physical and chemical processes to separate valuable minerals from waste material. This method can concentrate the desirable components (like silica and alumina) while reducing contaminants (like iron oxide). By applying beneficiation techniques to tailings, the overall quality of the ceramic products produced can be improved. This improves **efficiency** of up to 75% purity (Gupta and Yan, 2020**).**

3.15 Technological Scheme

A recommended scheme for tailings reprocessing include the following. This approach allows for flexible adaptation to different tailings compositions and economic conditions.

Tailings characterization → Dewatering and classification → Pre-concentration via gravity or flotation → Metal recovery using hydrometallurgical methods → Residue management.

For instance, gold-bearing tailings can be first treated using centrifugal concentrators, followed by cyanide-free leaching processes. This integrated scheme maximizes recovery while adhering to environmental standards. The use of mining tailings in producing construction materials demonstrates a strong case for sustainable resource management as shown in table 5.

Table 5: Proposed resources recovery model and traditional disposal method comparison

Features	Traditional Tailings Disposal	Proposed Resource Recovery Model
Waste Management Cost	High (>$2.5M/year)	Revenue-generating ($6.5M/year)
Environmental Risk	High (acid mine drainage)	Low (treated tailings)
Land Usage	Large tailings ponds	Small, modular processing plant
Product Output	None	Pipes, tiles, road materials
Employment	Minimal	Significant local employment
Sustainability	Low	High (circular economy)

3.16 Market Potential of Recovered Materials

Due to the trending global demand, tailings that contain especially copper, cobalt, lithium, and other rare earths, has surged due to the energy transition. Tailings that contain these minerals are becoming economically attractive (USGS, 2023). Table 6 illustrate the proposed envisaged economic model. Technologies such as froth flotation, bioleaching, and beneficiation have been adopted in Sweden's LKAB project, which reclaimed iron from tailings with high efficiency (Gupta and Yan, 2020). Moreover, the global green construction market is projected to grow at a CAGR of 10.3% by 2030 (Allied Market Research, 2022), increasing demand for sustainable materials. Costa Rica's construction industry, despite its preference for reinforced concrete, presents a niche market for aesthetic, lightweight ceramics derived from silica-rich tailings. At the same time, construction material demand is subject to regional infrastructure trends, interest rates fluctuations, and global supply chain pressures. For example, in post-COVID construction surges in Southeast Asia, the demand for alternative aggregates made from tailings increased sharply, but this trend may not hold in all economic contexts (Li et al., 2022). These fluctuations make long-term planning for tailings reuse projects inherently risky, requiring dynamic business models and publicprivate partnerships.

Furthermore, green-certified materials produced from tailings may attract a market premium in environmentally conscious sectors. The Model assumption presented in table 7 integrated plant processing of 3 products (pipes, tiles, road fill / construction) with modular units.

Table 6: Proposed economic feasibility model for the raw material

Parameter	Value
Initial investment	$3.2 million
Annual tailings processed	100,000 tonnes
Market value (products)	$6.5 million/year
Operating cost	$2.8 million/year
Payback period	3 years
Job creation	~100 direct, 250 indirect

4. Conclusion

This study has demonstrated that mine tailings, which is traditionally viewed as waste, possess significant potential for economic and environmental protection. By utilizing tailings into construction materials such as ceramics, tiles, bricks, and pipes, the mining sector can actively contribute to a circular economy while mitigating decades of long environmental liabilities. The findings indicate that with appropriate processing technologies such as flotation, beneficiation, and bioleaching substantial quantities of residual minerals can be recovered, reducing the need for virgin resource extraction and the risks associated with tailings storage. Moreover, market analysis revealed a growing demand for affordable green-certified building materials, suggesting strong commercial viability for tailings based products, especially in rapidly urbanizing and industrializing regions of the world.

The sustainability of construction and road materials depends significantly on selecting quality granular inputs, such as those rich in silica, alumina, and iron oxide, commonly found in mine residues. With global demand for aggregates rising, alternative materials from mining by-products offer a viable, sustainable solution. Proper on-site processing characterization, sorting, and treatment is essential to meet global performance standards. Promoting these alternatives aligns with sustainable development goals, conserves non-renewable resources, and requires supportive legal frameworks, including incentives and landfill taxes. Adoption of advanced processing technologies can spur innovation, attract investment, and stimulate economic growth, especially in mining regions, by creating jobs and enhancing local resilience through diversified economic activities.

Despite these promising outcomes, the study acknowledges certain limitations. The economic estimates are based on hypothetical data and may vary significantly depending on site specific mineralogy, market fluctuations, and standard regulatory frameworks. Additionally, technical feasibility can be constrained by heterogeneity in tailings composition, stakeholder resistance, and inadequate infrastructure in remote mining areas especially in developing countries.

Nevertheless, integrating mine tailings reuse into national mineral policies and aligning with Sustainable Development Goals (SDGs) such as responsible consumption and production (SDG 12) and climate action (SDG 13) can enhance global sustainability efforts. Encouraging legal frameworks, including landfill taxes and incentives for green innovation, coupled with investments in advanced processing technologies, can accelerate adoption. If these enablers are strategically leveraged, tailings valorisation can stimulate innovation, create local employment, and promote resilience in mining-dependent communities, reinforcing a just transition to a sustainable and inclusive mining future.

Recommendations and Future Work

Future works and research should focus on analysis of detailed geochemical and mineralogical characterization of diverse tailings sites to refine recovery methods and economic models. Pilot scale testing and life cycle assessments are needed to validate laboratory findings to quantify long term environmental benefits while understanding, impacts on carbon savings, and resource efficiency gains of various reuse scenarios. These analyses can help inform policy decisions, attract green investment, and shape certification standards for tailings-derived products. Furthermore, interdisciplinary studies combining geology, engineering, and socio-economic analysis will be crucial to developing tailored, scalable models for sustainable tailings reprocessing across different mining regions. Stakeholders in the mining industry including, but not limited to mining companies, regulators, research institutions, and community organizations must be strategically engaged in this transformation journey. Some specific recommendation are listed in table 8 below.

An engineering and scientific collaborative driven policy supported approach is essential to fully unlock the value of mine tailings as a resource, while ensuring environmental stewardship, economic viability, and social inclusion in mining-affected regions. Future research should also explore innovative processing technologies such as microwave-assisted leaching, biomineralization, or carbon sequestration via mineral carbonation.

Some specific recommendations to stakeholders in the mining Industry

Recommendations

1. Government and Regulators

- Develop legal frameworks and fiscal incentives (e.g., tax rebates and wavers, landfill taxes, green product certifications) to encourage tailings reuse.
- Mandate baseline environmental audits for inactive tailings facilities to identify valorisation opportunities.
- Mandate and Support technical training and capacity building programs for local engineers and processors.

2. Mining Companies

- Integrate tailings valorisation into mine closure and rehabilitation plans of companies.
- Invest in on-site pilot plants to test product development, such as bricks or ceramic tiles.
- Adopt digital tools (e.g., GIS and Remote sensing, and geospatial mapping) for tailings monitoring and material classification.
- Collaborate with other stakeholders construction companies to develop markets for tailings-based products.
- Support and provide research grants as sponsors to universities and institutes providing access to real time case studies.

3. Academia and Research Institutions

- Conduct interdisciplinary studies that combine geology, environmental science, materials engineering, and socio-economic analysis to design scalable reprocessing models.
- Establish knowledge-sharing platforms or databases to catalogue successful case studies and best practices globally.

4. Local Communities and NGOs

- Engage in participatory planning to ensure social acceptability and address concerns around safety, health, and employment.

- Advocate for community-owned micro-enterprises that could process tailings into affordable housing materials or infrastructure inputs.

References

Singh, R. P., Yadav, V., and Shukla, A., 2018. Utilization of mine tailings as construction material: A review. Environmental Earth Sciences, 77(6), Pp. 230. https://doi.org/10.1007/s12665-018-7392-5

Tebogo M and Thandiwe S., 2021. Clean production of sustainable backfill material from waste gold tailings and slag, Journal of Cleaner Production, V. 308, ISSN 0959 6526, https://doi.org/10.1016/j.jclepro.2021.127357. (https://www.sciencedirect.com/science/article/pii/S0959652621015766).

Tutu, H., McCarthy, T. S., and Cukrowska, E., 2020. Reuse of gold mine tailings for the production of bricks. Journal of Environmental Management, 259, 109687. https://doi.org/10.1016/j.jenvman.2019.109687.

Vitti, C and Arnold, B. J. 2022. The reprocessing and revalorization of critical minerals in mine tailings, Mining, Metallurgy and Exploration, Vol. 39, pp. 49–54.

Wang, J., Liu, Z., and Chai, H., 2023. AI-enhanced mineral sorting in tailings reprocessing: Application and prospects. Minerals, 13(4), Pp. 564.

World Bank., 2020. Mineral Resource Governance in the 21st Century: Gearing Extractive Industries Towards Sustainable Development.

You, Z., Zhao, Y., and Jin, Y., 2020. Application of tailings in reclamation: An overview. Journal of Cleaner Production, 244, 118789. https://doi.org/10.1016/j.jclepro.2019.118789

Yu, X., Kemeny, J., Tan, Y., Song W., and Huang. K., 2021. Mechanical properties and fracturing of rock-backfill composite specimens under triaxial compression. Construction and Building Materials, 304. https://doi.org/10.1016/J.CONBUILDMAT.2021.124577.

Zhang, W., Xu, Y., and He, B., 2012. Use of coal gangue and fly ash for brick production: review. Construction and Building Materials, 28(1), Pp. 450–456. https://doi.org/10.1016/j.conbuildmat.2011.08.074

Zhou, J., Kim, H., and Choi, D., 2022. Smart technologies in tailings reprocessing: Review and outlook. Journal of Cleaner Production, 347, 131245.

Zhuang P, McBride MB, Xia H, Li N, Zhian Li., 2009. Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China. Sci Total Environ 407:1551–1561

Zhuang, X., Zuo, Z., Yang, Y., and Qin, W., 2021. Recovery of valuable metals from tailings using hydrometallurgical technologies: A review. Minerals Engineering, 168, 107973. https://doi.org/10.1016/j.mineng.2021.107973.