© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719663

Circular Use of Mining Raw Materials: Recovery of Valuable Minerals from Tailings and Fine Particles in Saudi Arabia

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Abstract- This review examines the circular use of mining raw materials through recovery of valuable minerals from tailings and fine particles in Saudi Arabia. The paper follows recent review-paper conventions by combining structured literature selection, technology comparison, and Saudi-specific interpretation. Tailings are no longer treated only as liabilities; they are secondary resource bodies containing residual phosphates, base metals, rare earth elements, gold-associated minerals, barite, manganese, and other value carriers that may support Vision 2030 industrial diversification. Drawing on studies published between 2020 and 2025, the review evaluates fine-particle beneficiation, flotation re-cleaning, gravity and magnetic pre-concentration, hydrometallurgical leaching, bioleaching, solvent extraction, precipitation, dewatering, and residue valorisation. The aim is to propose a practical, staged framework for Saudi mines, where mineralogical characterization is linked to water-efficient processing, environmental risk reduction, and downstream industrial use. The paper argues that the strongest opportunity is not a single recovery technology, but an integrated geometallurgical pathway that grades tailings, identifies recoverable mineral phases, selects low-water separation options, and converts final residues into safer construction, backfill, or rehabilitation materials. The review concludes with research priorities for pilot testing, digital tailings inventories, life-cycle assessment, and investment decision rules.

Keywords: Tailings Reprocessing, Critical Minerals, Fine Particles, Saudi Arabia, Circular Economy, Hydrometallurgy, Flotation, Vision 2030

I. INTRODUCTION

Mining is entering a new resource era in which waste is being redefined as a strategic reserve. Conventional ore bodies are declining in grade, while the demand for metals used in batteries, renewable energy, electronics, fertilizers, infrastructure, and advanced manufacturing continues to increase. Recent reviews show that mine and mineral-processing tailings can contain unrecovered critical and valuable metals because historic circuits were designed around a limited number of products rather than full-resource utilization (Kursunoglu, 2025; Sarker et al., 2022).

In Saudi Arabia, this issue has immediate relevance. The Kingdom is developing mining as a third industrial pillar under Vision 2030, expanding phosphate, gold, copper, zinc, bauxite, industrial minerals, and future critical-mineral value chains. A circular approach to tailings can therefore reduce environmental liabilities while adding secondary feedstocks to domestic mineral supply.

Tailings and fine particles are challenging because they are compositionally heterogeneous, water-rich, and often dominated by ultrafine minerals that respond poorly to conventional separation.

However, these same materials may host liberated or partially liberated value minerals that were lost because older circuits lacked sufficient selectivity, reagent control, particle-size targeting, or downstream hydrometallurgical recovery (Abbadi & Mucsi, 2024; Nakhaei et al., 2024).

The Saudi context adds further constraints: arid climate, high evaporation, water scarcity, large transport distances, and the need to protect groundwater and desert ecosystems. These constraints make dry or low-water pre-concentration, closed-loop water management, paste thickening, and residue stabilization central to any tailing's recovery strategy.

The purpose of this review is to synthesize recent knowledge on recovering valuable minerals from tailings and fine particles and translate it into a Saudi mining pathway.

Unlike studies that focus only on one metal or one method, this paper integrates mineralogical diagnosis, beneficiation, hydrometallurgy, environmental risk, and economic feasibility.

The review addresses four questions: which minerals are most plausible for recovery from Saudi tailings; which technologies are suitable for fine particles; how can environmental risks be reduced while recovering value; and what research agenda is needed to move from laboratory studies to pilot-scale implementation.

II. AIM, OBJECTIVES AND REVIEW SCOPE

The aim of the study is to develop a review-based circular recovery framework for valuable minerals in Saudi mining tailings and fine particles. The study is built around five objectives. First, it explains why tailings should be evaluated as secondary raw materials rather than passive waste. Second, it reviews recent recovery technologies applicable to fine and ultrafine particles.

Third, it evaluates environmental and economic conditions that influence adoption in arid Saudi operations. Fourth, it maps the recovery pathway to Vision 2030 priorities for resource efficiency, industrial localization, and sustainable mining. Fifth, it identifies research gaps for future pilot studies, especially in phosphate, gold, copper-zinc, and industrial-mineral tailings.

The scope is a narrative and semi-systematic review rather than a laboratory experiment. The emphasis is on papers published from 2020 to 2025, because this period reflects rapid advances in critical-mineral policy, hydrometallurgical selectivity, circular-economy assessment, and tailings governance.

The attached Springer review model uses structured literature selection, technology grouping, graphical synthesis, and tabulated comparisons; the same logic is adopted here but redirected toward Saudi Arabia and the circular recovery of tailings and fine particles (Kursunoglu, 2025).

III. METHODOLOGY: STRUCTURED LITERATURE REVIEW

A structured review methodology was designed to ensure academic traceability and practical relevance. Search terms combined three clusters: tailings and fine particles; recovery technology; and Saudi or arid-region mining.

Examples included 'mine tailings recovery', 'critical minerals from tailings', 'fine particle flotation', 'hydrometallurgical recovery from mine waste', 'bioleaching tailings', 'phosphate tailings circular economy', 'Saudi mining Vision 2030', and 'tailings dewatering'.

The preferred databases and publisher platforms were ScienceDirect, SpringerLink, MDPI, Taylor & Francis, and Web of Science-indexed journals. Policy and industry context was taken from Vision 2030, mining-sector sources, and international critical-mineral reports.

The inclusion criteria were: publication between 2020 and 2025; direct relevance to metal or mineral recovery from tailings, mine waste, acid mine drainage, or fine particles; methodological clarity; and discussion of environmental, economic, or circular-economy outcomes. Studies were excluded if they focused only on primary ore mining without waste recovery, lacked process evidence, or were unrelated to mineral processing.

The review then classified literature into six themes: geometallurgical characterization; physical beneficiation; flotation and fine-particle recovery; hydrometallurgy and precipitation; bio-based recovery; and environmental-economic assessment. This structure supports a balanced review consistent with Scopus, Elsevier, Springer, and Emerald-style expectations.

The methodology also used a technology-readiness interpretation. Each recovery route was evaluated against five Saudi implementation criteria: water demand, selectivity for fine particles, tolerance of complex mineralogy, environmental risk reduction, and potential for integration with existing mines.

This approach is suitable because Saudi tailings recovery is not simply a metallurgy question; it is an industrial systems question involving energy, water, logistics, permits, residue safety, and downstream market demand.

Figure 1. Apple-inspired circular recovery framework for tailings and fine particles in Saudi Arabia.

IV. SAUDI MINING CONTEXT AND CIRCULAR-ECONOMY RELEVANCE

Saudi Arabia has significant mineral potential across phosphate, bauxite, gold, copper, zinc, silica, feldspar, magnesite, barite, and industrial minerals. Large-scale phosphate operations in the north, gold and base-metal districts in the Arabian Shield, and expanding exploration programs create both opportunity and responsibility. Every beneficiation plant produces tailings streams, slimes, sludges, or low-grade fines.

Historically, many of these materials were stored because the primary objective was recovery of the main commodity. A circular mining model changes the question from 'what is waste?' to 'which fraction still contains recoverable value, and how can the remaining residue be made safer?' (Jose et al., 2024; Mancini et al., 2024).

Tailings valorisation fits Saudi Vision 2030 in three ways. First, it improves resource efficiency by extracting more value from material already mined, crushed, ground, and transported. Second, it supports local supply chains for industrial inputs, including fertilizers, construction materials, metals, and potentially critical minerals.

Third, it lowers environmental liability by reducing acid generation, seepage risks, dust, and land-use pressure when coupled with improved storage and rehabilitation. The strategic value is particularly high where tailings contain phosphate-associated rare earth elements, residual copper-zinc sulphides, gold-bearing fines, manganese, barite, or silica-alumina phases suitable for engineered products.

Saudi conditions also require adaptation. Water scarcity makes conventional wet reprocessing expensive unless water is recycled through high-rate thickeners, paste disposal, filtration, or dry stacking. Fine desert dust and saline water chemistry may affect reagents and flocculants.

High solar potential, however, can support lower-carbon process energy, remote monitoring, and sensor-based sorting infrastructure. The best Saudi pathway is therefore likely to combine dry characterization, selective wet stages only where justified, closed-loop process water, and residue conversion into backfill, cementitious additives, road-base materials, or stabilized landforms.

V. NATURE OF TAILINGS AND FINE PARTICLES

Tailings are not uniform waste; they are engineered geological materials shaped by ore mineralogy, comminution, reagents, water chemistry, and historical plant performance. Fine particles below roughly 38 micrometers are especially important because they may hold significant residual metals but have low collision efficiency in flotation and slow settling in thickeners. Ultrafines may also carry clay minerals, iron oxides, carbonates, sulphides, or phosphate slimes that consume reagents and trap value minerals.

Recent studies emphasize that successful recovery begins with mineralogical characterization rather than immediate process selection (Sarker et al., 2023; Nwaila et al., 2021).

For Saudi phosphate tailings, potential targets include residual apatite, rare earth elements associated with phosphate minerals, fluorine-bearing phases, and carbonate-rich residues. For gold and polymetallic tailings in the Arabian Shield, targets may include fine free gold, sulphide-hosted copper, zinc, lead, silver, and trace critical elements.

For bauxite and aluminosilicate residues, the opportunity may involve iron, titanium, rare earths, or construction-material valorisation. The exact opportunity depends on particle-size distribution, liberation, deportment, and element concentration. Therefore, a national tailings inventory should include chemical assays, mineral mapping, size-by-size metal distribution, acid-generation tests, moisture content, and storage stability.

Fine-particle recovery also requires recognition of losses created by conventional circuits. Valuable minerals may be lost as locked composites, surface-oxidized particles, slimes coatings, reagent-depressed grains, or particles too fine to attach to bubbles. These mechanisms explain why reprocessing should not simply repeat the original plant flowsheet.

It should use new diagnostics such as automated mineralogy, laser particle sizing, sequential extraction, hyperspectral scanning, and bench-scale tests that identify the most recoverable fraction before full-scale treatment.

Table 1. Major Saudi tailings streams and plausible circular recovery opportunities

Tailings / fines stream	Likely value carriers	Recommended recovery focus	Circular benefit
Phosphate slimes	Apatite, REE-bearing phosphate phases, carbonates	Desliming, column flotation, deportment-led leaching	Improves fertilizer value chain and reduces slurry footprint
Gold tailings	Fine free gold, pyrite-hosted Au, Ag, As/Sb phases	Gravity scavenging, sulphide flotation, selective leaching research	Adds precious-metal recovery and safer closure
Copper-zinc tailings	Chalcopyrite, sphalerite, galena, pyrite, trace In/Ge	Re-cleaning flotation, acid/oxidative leaching, residue stabilization	Supports base-metal supply and reduces sulphide risk
Industrial mineral fines	Barite, silica, aluminosilicates, carbonates	Classification, magnetic separation, binder/geopolymer tests	Creates construction inputs and lowers disposal demand

VI. RECOVERY TECHNOLOGIES FOR VALUABLE MINERALS

Physical pre-concentration is often the first step because it can reduce the mass that requires chemical treatment. Gravity separation is suitable for dense minerals such as gold, wolframite, barite, and heavy mineral concentrates, although efficiency decreases as particles become ultrafine.

Magnetic separation can remove magnetite or concentrate iron-bearing phases and may help upgrade rare-earth-bearing monazite when combined with electrostatic separation (Echeverry-Vargas et al., 2022). Sensor-based sorting is less useful for slimes but valuable for coarser legacy waste, low-grade stockpiles, and dry pre-concentration before grinding.

Flotation remains essential for sulphide and phosphate tailings. Re-cleaning can recover residual copper, zinc, lead, pyrite-associated gold, and apatite if surface chemistry is managed correctly.

For fine particles, improvements include microbubble flotation, column flotation, carrier flotation, selective flocculation, and reagent schemes that reduce entrainment of gangue. Recent work on sulphide tailings shows that mineralogical deportment determines whether flotation should target base metals, precious metals, or critical elements (Gibson et al., 2023; Nakhaei et al., 2024).

In Saudi Arabia, column flotation and enhanced phosphate flotation are particularly relevant because they offer better selectivity for fine particles and lower gangue entrainment.

Hydrometallurgy is the strongest option where valuable elements are too finely disseminated for physical separation. Acid leaching, alkaline leaching, chloride systems, organic acids, pressure leaching, solvent extraction, ion exchange, and selective precipitation can recover metals from complex matrices.

Studies demonstrate recovery of rare earths from acid mine drainage sludge, copper and zinc from polymetallic tailings, antimony from stibnite tailings, and manganese-cobalt-nickel from mine drainage solutions (Cicek et al., 2023; Dembele et al., 2024; Javanshir et al., 2024; Li & Zhang, 2022).

For Saudi mines, hydrometallurgy must be selective and water-efficient; uncontrolled acid use could create secondary contamination or high neutralization costs.

Bioleaching and bio-oxidation offer lower-temperature alternatives for sulphide tailings. Microorganisms can oxidize sulphides and mobilize metals, which may be attractive for low-grade materials where conventional leaching is uneconomic.

Bioleaching is slower than chemical leaching and sensitive to salinity, temperature, and pH, but Saudi solar energy and controlled heap or bioreactor systems may support hybrid models. Studies on low-grade ores and tailings show that biohydrometallurgy can reduce reagent intensity while improving access to metals trapped in sulphide matrices (Nkuna et al., 2022; Chaerun et al., 2023).

Residue valorisation is the final recovery stage. Once metals are extracted, remaining solids may be used in cement, geopolymer binders, mine backfill, ceramic materials, road bases, or rehabilitation covers if they meet safety standards.

This is vital because circular mining should not produce a second waste problem. Dewatering technologies, including paste thickening, filtration, and advanced flocculation, can recover water and create stable residues for reuse (Adewuyi et al., 2024; Hamraoui et al., 2024).

VII. INTEGRATED SAUDI RECOVERY FRAMEWORK

The proposed framework begins with a digital tailings inventory. Each tailings storage facility should be mapped by age, source ore, volume, water content, geochemistry, mineralogy, particle size, and environmental risk.

The second step is geometallurgical ranking, where tailings are divided into high-value, medium-value, and stabilization-only categories. High-value tailings proceed to beneficiation and hydrometallurgical testing; medium-value tailings may be blended or treated using low-cost pre-concentration; stabilization-only residues are prioritized for dewatering, cover systems, dust control, and safe reuse.

The third step is process selection. Phosphate-rich tailings may require desliming, flotation, rare-earth deportment studies, and acid or organic leaching tests. Gold tailings may require gravity concentration, intensive cyanide alternatives where permitted, thiosulfate or glycine research, and sulphide flotation.

Copper-zinc tailings may use flotation re-cleaning followed by targeted leaching. Industrial-mineral fines may be screened for silica, barite, calcium carbonate, or aluminosilicate reuse. The fourth step is life-cycle sustainability assessment, because the best metallurgical recovery is not always the best circular option if it consumes excessive water, acid, energy, or transport.

The fifth step is pilot demonstration. Saudi mining companies should avoid moving directly from laboratory extraction results to commercial investment. Pilot plants should test seasonal water chemistry, dust control, residue stability, reagent recycling, and product quality.

The output should be a bankable recovery model that includes capital expenditure, operating expenditure, product markets, waste reduction, carbon intensity, and permitting requirements. This staged framework reduces technical uncertainty and aligns tailings recovery with responsible investment.

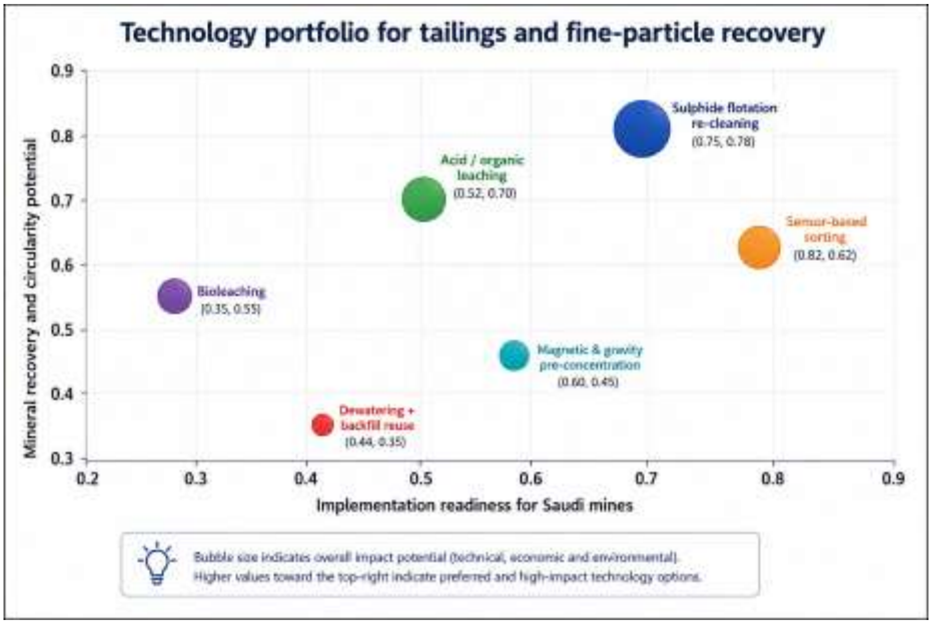

Figure 2. Technology portfolio matrix for Saudi tailings recovery and circular residue use.

VIII. ENVIRONMENTAL AND ECONOMIC ASSESSMENT

Tailings recovery is attractive only when environmental and economic benefits are evaluated together. Environmental benefits include reduced metal leaching, lower acid-generation potential, smaller tailings footprints, recovered process water, reduced dust, and safer closure designs.

Economic benefits include additional metal products, avoided rehabilitation costs, extended mine life, and lower demand for newly mined primary ore. However, the process can become unsustainable if low-grade material requires excessive grinding, long-distance transport, high acid consumption, or complex effluent treatment (Di Maria et al., 2024; Yu et al., 2024).

Saudi Arabia's arid environment means water accounting must be central to feasibility. A process that recovers copper or rare earths but loses large volumes of water may be weaker than a slightly lower-recovery process with closed-loop water recycling. Similarly, residue chemistry must be assessed before reuse in construction or backfill. Materials containing arsenic, sulphides, fluorides, or soluble salts require stabilization and leachability testing.

Circularity should therefore be measured by net recovered value, net risk reduction, and net resource savings, not by recovery percentage alone.

Economic evaluation should begin with cut-off logic for secondary resources. Tailings may be profitable when they are already mined and ground, but they may still require dredging, pumping, dewatering, regrinding, reagents, energy, and new storage capacity.

A realistic model should include sensitivity analysis for metal prices, reagent costs, water costs, carbon cost, product penalties, and closure liability. Saudi projects are more likely to succeed when recovery products connect to domestic demand, such as phosphate fertilizers, battery materials, construction binders, copper supply chains, or industrial minerals.

Table 2. Review-method screening matrix for technology selection

Criterion	Low suitability indicator	High suitability indicator	Saudi decision implication
Water intensity	Single-pass wet circuit, high bleed stream	Closed-loop water, paste thickening, filtration	High priority because of arid conditions
Fine-particle selectivity	High entrainment or poor liberation	Column flotation, selective flocculation, targeted leaching	Controls recovery from slimes and ultrafines
Environmental risk	Acid-generating residue or soluble contaminants	Stabilized residue, reduced leachability, safe reuse	Supports permitting and closure confidence
Economic resilience	Dependent on one volatile metal	Multiple products plus avoided closure cost	Improves investment case under price changes
Industrial integration	No local product outlet	Linked to fertilizers, metals, backfill, binders	Strengthens Vision 2030 localization

IX. RESEARCH GAPS AND FUTURE DIRECTIONS

The first research gap is the limited public database on Saudi tailings composition. A national tailings resource atlas would help prioritize facilities for recovery, rehabilitation, and monitoring. The atlas should combine satellite mapping, drone surveys, geochemical sampling, and mineralogical analysis.

The second gap is fine-particle technology under Saudi water chemistry. Many published flotation and leaching results are based on laboratory water, while actual plants may use saline groundwater, recycled process water, or high-sulfate water that changes reagent behavior.

The third gap is rare-earth recovery from phosphate-associated materials. Saudi phosphate resources may contain rare earth elements at low concentrations, and recovery will require careful deportment studies, acid consumption control, impurity management, and integration with fertilizer processes.

The fourth gap is circular use of final residues. More research is needed on geopolymerization, cement replacement, road-base durability, radiation screening, and long-term leaching performance under Saudi heat and salinity.

The fifth gap is digital monitoring. Tailings recovery should be connected to sensors, process analytics, and environmental dashboards that track water recovery, seepage risk, dust, and product quality in real time.

Future research should also compare technologies using standardized indicators. These should include recovery percentage, concentrate grade, water intensity, energy intensity, reagent intensity, residue hazard class, carbon footprint, cost per tonne treated, and social acceptance.

Such indicators would allow Saudi regulators, investors, and mining companies to compare options transparently and accelerate responsible commercialization.

X. CONCLUSION

The circular use of mining raw materials offers Saudi Arabia a practical route to increase mineral value while reducing environmental liability. Tailings and fine particles should be treated as secondary resource systems requiring careful characterization, not as homogeneous waste.

The strongest recovery pathway is integrated: digital inventory, geometallurgical ranking, selective beneficiation, targeted hydrometallurgy or bioleaching, water recovery, and residue valorisation. This approach is particularly relevant to phosphate, gold, copper-zinc, and industrial-mineral operations.

The review shows that technologies from 2020 to 2025 have matured rapidly, but successful Saudi implementation will depend on local adaptation. Water-efficient circuits, saline-water testing, fine-particle flotation, selective leaching, paste dewatering, and safe residue reuse should become core research priorities.

Tailings recovery can support Vision 2030 by strengthening domestic mineral supply chains, lowering waste risk, and creating new industrial materials from resources already extracted. The next step is pilot-scale demonstration supported by transparent environmental and economic metrics.

XI. IMPLEMENTATION ROADMAP FOR SAUDI TAILINGS RECOVERY

For practical implementation, the first priority is to establish a Saudi tailings registry that treats each storage facility as a potential resource and risk asset. The registry should record tonnage, depth, deposition history, process source, reagent history, water chemistry, ownership, access, and closure status.

It should also include a confidence rating, because not every facility will have the same level of sampling or documentation. The registry would allow companies and regulators to rank sites for immediate recovery, monitoring, or rehabilitation. It would also prevent duplicate sampling campaigns and support investor screening before costly pilot work begins.

The second priority is sampling discipline. Tailings are deposited over time, so vertical and horizontal variability can be substantial. A single surface sample is not enough for investment decisions. Saudi projects should use sonic drilling, trenching where safe, drone topography, geophysical mapping, and compositional domaining.

Samples should be separated by size fraction because fine slimes and coarser sands may contain different value minerals. Each fraction should be tested for grade, mineral liberation, reagent response, acid generation, salinity, and settling behavior. This approach creates a geometallurgical model rather than a simple assay report.

The third priority is water-smart testing. Bench studies should report water source, ionic strength, pH, sulfate, chloride, carbonate alkalinity, and recycled-water effects. Many flotation and leaching papers report strong recoveries under clean laboratory conditions, but plant water may change bubble stability, depressant performance, collector adsorption, flocculation, and metal solubility.

For Saudi Arabia, this difference is critical. A promising circuit should be repeated with representative site water and with progressively recycled process water. Only then can the recovery rate be considered operationally reliable.

The fourth priority is to combine recovery with hazard reduction. A project that recovers one valuable product but leaves a more reactive residue does not meet circular-economy expectations.

Every recovery route should therefore include pre-treatment and post-treatment leachability tests, acid-base accounting, kinetic column tests, dusting tests, and residue stabilization options.

If sulphides are removed by flotation, the desulphurized residue may become safer for dry stacking or construction use. If acid leaching is applied, neutralization sludge must be characterized and managed as a new residue stream.

The fifth priority is product-market validation. Tailings recovery is not complete when a concentrate is produced; it becomes circular only when the product enters a reliable value chain.

Phosphate concentrates must meet fertilizer specifications. Copper or zinc products must meet smelter penalty limits. Rare-earth intermediates must be clean enough for separation or sale. Silica, carbonate, barite, and aluminosilicate residues must meet construction or industrial standards.

Saudi pilot projects should therefore include buyers, fertilizer producers, cement companies, and metal processors early in the design stage.

The sixth priority is modular pilot design. Mobile or containerized pilot plants can test multiple tailings facilities without building permanent infrastructure too early.

A modular plant may include classification, attrition, column flotation, magnetic separation, thickening, filtration, leaching tanks, solvent extraction skids, and water-treatment units.

Data from such pilots would help determine whether the opportunity should be scaled as a stand-alone reprocessing plant, integrated into an existing concentrator, or treated as a campaign-based recovery operation.

The seventh priority is digital monitoring. Tailings recovery should use sensors for density, particle size, pH, oxidation-reduction potential, conductivity, turbidity, dissolved metals, and water return.

Machine-learning models can connect these indicators to grade, recovery, reagent consumption, and residue quality.

Digital dashboards would help plant teams control variability and would give regulators transparent evidence that water, dust, and seepage risks are being managed. In remote Saudi mining areas, this capability is especially valuable because it reduces reliance on delayed manual reporting.

The eighth priority is a decision gate system. Gate one should confirm that a tailings facility contains recoverable value or a major risk-reduction opportunity. Gate two should prove technical recovery at bench scale. Gate three should validate water balance and residue safety at pilot scale.

Gate four should confirm product offtake and economic resilience. Gate five should approve commercial deployment only if the project reduces net environmental risk and creates positive resource value. This staged discipline would protect investors and communities from over-promising based on laboratory extraction alone.

The Saudi research community can support this agenda through university-industry test centers focused on fine-particle recovery, phosphate tailings, saline-water flotation, rare-earth deportment, and low-carbon hydrometallurgy.

Joint research with operating mines would generate site-specific data while developing local expertise. This is important because imported technology cannot simply be copied into Saudi conditions without adaptation. Local mineralogy, climate, water chemistry, logistics, and product demand must shape the final process design.

Policy support is also necessary. Regulators could encourage tailings valorisation by requiring recoverability screening in closure plans, recognizing reprocessed tailings as secondary raw materials when safety criteria are met, and creating clear approval routes for pilot plants.

Incentives may be justified where projects reduce long-term environmental liabilities or recover materials aligned with strategic industrial priorities. At the same time, regulation must prevent unsafe reuse of contaminated residues. Circularity should be evidence-based, not a label applied to any waste movement.

Overall, the most credible route for Saudi Arabia is selective circularity. Some tailings will justify metal recovery, some will justify water recovery and stabilization, and others will justify reuse as construction or backfill material after testing. A mature system will choose the pathway that produces the greatest combined benefit: resource value, water savings, risk reduction, and industrial usefulness. This practical interpretation allows tailings to become part of Saudi Arabia's mining growth strategy while respecting environmental limits.

A disciplined recovery roadmap strengthens resource security, lowers closure risk, conserves scarce water, supports local manufacturing, improves environmental confidence, and gives Saudi decision makers clear evidence for responsible investment A disciplined.

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