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DECEMBER 2025

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EXECUTIVE SUMMARY

The United States faces an acute strategic vulnerability in its dependence on foreign sources, particularly geopolitical adversaries, for critical minerals essential to national defense, energy security, and advanced manufacturing. These materials, including rare-earth elements (REEs), lithium, cobalt, gallium, and others, form the foundation of technologies: precision-guided munitions, fighter-jet engines, energy-storage devices, and cell phones [1]. Current U.S. import reliance exceeds 50% for more than half of the 50 minerals designated as critical, and China dominates both extraction and processing for many of these strategic materials [2]. This dependence threatens not only economic competitiveness, but also the ability to maintain technological superiority and respond to national security challenges.

This report presents a comprehensive technical assessment of a promising yet underutilized domestic resource: the billions of tons of mine tailings generated by more than a century of hardrock mining across the United States. These waste materials, historically viewed as environmental liabilities, contain recoverable quantities of critical minerals that were either not economically valuable during initial mining operations or technically difficult to extract with past-generation processing technologies. Recent collaborative efforts between the Department of Energy's (DOE's) National Energy Technology Laboratory and Idaho National Laboratory (INL) have documented over 300 datasets from more than 100 sources characterizing these tailings, representing more than 10 gigabytes of information on critical-mineral content in mine waste [3]. Preliminary analysis indicates that domestic mine tailings from the top ten commodity types contain an estimated 13,904 MMT of material across 189 major sites, with significant concentrations of such critical minerals as REEs, cobalt, gallium, germanium, indium, and platinum-group elements [3,4]. While coal-based resources also represent a significant potential source of critical minerals and have been the subject of substantial DOE research and demonstration programs, they are explicitly excluded from this analysis. Other DOE supported organizations are examining coal-based critical-mineral recovery potential, and those analyses should be consulted for comprehensive understanding of that opportunity.

The potential of mine tailings as a secondary source extends across diverse deposit types. Copper-gold porphyry systems, which dominate Arizona's mining landscape at facilities such as Sierrita, Bagdad, and Morenci, contain not only residual copper but also gallium, germanium, cobalt, and indium in their tailings [3]. Epithermal gold deposits across Nevada, Montana, and South Dakota generated tailings enriched in indium. Lead-zinc operations, particularly in Missouri's Old Lead Belt, left behind materials containing cobalt, nickel, and germanium [3]. Phosphate-mining operations in Idaho and Florida produced waste streams containing REEs, uranium, and thorium [5]. Even historical uranium-mining districts such as the Grants Mineral Belt in New Mexico and the Uravan Mineral Belt spanning Colorado and Utah generated tailings with vanadium, selenium, and molybdenum content [5]. This diversity of deposit types provides multiple pathways to develop domestic critical-mineral supplies from secondary sources.

The strategic appeal of recovering critical minerals from mine tailings extends beyond supply security to encompass significant environmental and economic co-benefits. Many legacy tailings sites represent ongoing pollution sources through acid mine drainage, heavy-metal leaching, and dust generation. Reprocessing these materials offers the opportunity to simultaneously extract valuable minerals and remediate environmental hazards by removing the hazardous components entirely and/or consolidating the remaining waste into modern engineered storage facilities with proper environmental controls. Economic modeling suggests that tailings reprocessing can achieve lower operational costs than primary mining for certain minerals because the energy-intensive steps of rock excavation and initial comminution have already been completed [6]. Furthermore, these projects can provide economic revitalization for former mining communities, particularly in regions experiencing declines in traditional mining employment.

Despite this potential, significant barriers impede the large-scale development of critical-mineral recovery from mine tailings. The most-fundamental challenge is incomplete site characterization. While researchers have identified hundreds of datasets, fewer than 10% provide sufficient detail for immediate project development and investment decisions [3]. Most existing data require extensive processing, including digitization of scanned documents, georeferencing, and laboratory validation. The absence of a comprehensive, standardized national database of tailings sites with verified critical-mineral content creates substantial uncertainty for private-sector developers attempting to identify and evaluate potential projects. This data gap represents the single most-critical barrier to accelerating deployment of tailings-recovery technologies.

Protracted permitting timelines—historically characterized by National Environmental Policy Act (NEPA) environmental impact statements (EISs) taking a median of roughly 4–5 years, with total project permitting often extending even longer—and liability concerns under the Comprehensive Environmental Response, Compensation, and Liability Act have been major barriers to project development; recent statutory reforms now establish presumptive limits of 2 years for EISs and 1 year for environmental assessments (EAs) [3,7]. Economic barriers include the technical complexity of separating multiple critical minerals from complex matrices, volatile commodity prices that create investment risk, and the high upfront capital requirements of processing facilities capable of handling large material volumes necessary to achieve economies of scale. The phenomenon of “companionality,” where 61% of evaluated metals are primarily produced as byproducts rather than primary commodities, further complicates supply dynamics. Companion-metal production depends heavily on host-metal mining economics, rather than responding directly to companion-metal demand [8].

Addressing these barriers requires coordinated federal action across multiple dimensions. This report presents nine key recommendations to accelerate critical-mineral recovery from domestic mine tailings. The foundational recommendation calls for a National Mine Tailings Assessment Program to systematically characterize tailings sites across all major U.S. mining districts within 12–18 months. This would create a publicly accessible database that would enable efficient site identification and project screening. Regulatory reforms should include implementing the Good Samaritan Remediation of Abandoned Hardrock Mines Act (enacted Dec. 2024) with Environmental Protection Agency's 2025 guidance and pilot permits [9] for entities conducting approved remediation and mineral recovery at legacy sites, streamlining NEPA reviews for remediation-linked projects, and updating mining laws to clarify ownership and royalty treatment for minerals recovered from waste materials. Financial mechanisms should encompass production tax credits for critical minerals recovered from secondary sources, investment incentives for construction of processing facilities, and government offtake agreements that provide price stability and guaranteed markets for initial commercial production.

The United States can strengthen public-private partnerships by expanding the role of national laboratories in providing advanced separation-science expertise, analytical capabilities, and pilot-scale testing facilities to reduce technical risk for industry partners. Robust environmental and community safeguards must accompany accelerated development, including mandatory final site-remediation plans, performance bonding requirements, community-benefit agreements, and meaningful tribal consultation. Expanded research, development, and demonstration programs should advance extraction technologies for specific mineral-matrix combinations while proving economic viability at scale. Finally, strategic use of government procurement and the Defense Production Act can create stable demand signals that justify private investment in domestic recovery capacity.

The convergence of accelerating energy deployment, intensifying strategic competition, and growing defense-technology demands creates an urgent imperative to secure domestic critical-mineral supplies. Mine tailings represent a largely untapped domestic resource that, with appropriate policy support and strategic investment, can meaningfully contribute to supply-chain resilience while remediating legacy environmental liabilities and supporting economic development in mining-affected communities. The technical capabilities exist; the resource is documented; the strategic need is clear. What remains is coordinated federal action to remove barriers, de-risk investment, and expand the role of national laboratories to enable the transformation of yesterday's mining waste into tomorrow's strategic resources. The recommendations in this report provide a roadmap to achieve this transformation while maintaining prudent environmental standards and ensuring benefits flow to affected communities.

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CONTENTS

ACRONYMS

BLM	Bureau of Land Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CRADA	Cooperative Research and Development Agreement
DOE	Department of Energy
DoW	Department of War
DPA	Defense Production Act
EA	Environmental assessments
EIS	Environmental impact statement
EPA	Environmental Protection Agency
FAST	Fixing America's Surface Transportation
INL	Idaho National Laboratory
MRI	Mapping Resources Initiative
NEPA	National Environmental Policy Act
REE	Rare-earth elements
USGS	U.S. Geological Survey

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Critical-Minerals Recovery from Mine Tailings: A Technical Review and Strategic Assessment

1. INTRODUCTION

1.1. Critical Minerals: Definition and Strategic Importance

The Energy Act of 2020 defined a critical mineral as a non-fuel mineral or mineral material that serves an essential function in the economic or national security of the nation, faces a high risk of supply-chain disruption, and has no easy substitutes [10]. This definition has been refined through subsequent federal assessments and distinguishes critical minerals from other commodities by emphasizing both their indispensability to modern economic activity and their vulnerability to supply interruptions. The U.S. Geological Survey (USGS) maintains and periodically updates the official list of critical minerals, which in 2022 included 50 distinct minerals and mineral-material groups [11]. In 2025, the USGS expanded this list to 60 minerals, adding notable commodities such as metallurgical coal, uranium, phosphate, copper, lead, silver, rhenium, potash, silicon, and boron [12]. These materials span a remarkable diversity of applications and geological occurrences, from the rare-earth elements (REEs) essential for permanent magnets in electric motors, lithium and cobalt for advanced batteries, gallium and germanium for semiconductor manufacturing, platinum-group elements for catalytic converters and fuel cells, to uranium for nuclear energy production.

The strategic importance of critical minerals extends across three interconnected domains that together define modern economic and military power. In the defense sector, critical minerals enable precision guidance systems, advanced radar, electronic-warfare capabilities, and propulsion technologies that underpin contemporary military superiority. A single F-35 fighter aircraft, for example, contains large quantities of REEs and other critical minerals in its airframe, engines, and electronic systems [13]. Advanced munitions, satellite systems, and naval vessels similarly depend on specialized materials, the performance characteristics of which cannot be replicated with conventional alternatives. The economic domain encompasses both established industries and emerging technologies. Semiconductor manufacturing, which forms the foundation of the digital economy, relies on high-purity gallium, germanium, and rare-earth compounds. The move toward energy independence and security has heightened the importance of diverse domestic energy sources, including nuclear power, advanced coal technologies, and natural-gas production, all of which require critical minerals such as uranium for nuclear reactors, metallurgical coal for steel production used in energy infrastructure, and REEs for energy-efficient technologies [14]. The strategic imperative to secure domestic supplies of these materials has led to significant federal policy actions, including the expansion of the USGS Critical Minerals List to 60 minerals in 2025, with uranium and metallurgical coal specifically designated based on their importance to energy security and defense [12]. Advanced manufacturing sectors, including aerospace, telecommunications, and medical devices, have become increasingly dependent on critical minerals as product sophistication has grown.

The third strategic dimension involves technological leadership and innovation capacity. Nations that secure reliable access to critical minerals can pursue aggressive technology-development programs without concern for material constraints while those dependent on potentially hostile suppliers face the prospect of supply denial as a tool of economic coercion or geopolitical leverage. This reality has become increasingly apparent as China has consolidated control over global critical-mineral supply chains, from mining and processing to manufacturing of intermediate and finished goods. China’s dominance is not primarily a result of geological advantage as many critical minerals exist in economically viable concentrations across diverse global locations; rather, it reflects decades of strategic investment, acceptance of environmental externalities, and deliberate policy choices to capture value-added processing stages [15].

1.2. U.S. Supply Vulnerability and Import Dependence

According to USGS, the United States is 100% net import reliant for 12 commodities and over 50% import reliant for another 29 [16]; for rare earths, specifically, China provides roughly 70% of global mine output and about 90% of processing capacity [17]. This dependence represents a dramatic shift from the mid-20th century when domestic mining and processing operations supplied the majority of mineral needs for both industrial and defense applications. The transformation occurred gradually over several decades as a combination of factors—including more stringent environmental regulations, rising labor costs, declining ore grades in mature districts, and deliberate foreign competition—made domestic production economically challenging for many commodities. The closure of mines and processing facilities created a self-reinforcing cycle: as domestic expertise and infrastructure declined, the ability to respond to changing market conditions or strategic imperatives diminished correspondingly.

The concentration of supply sources compounds the vulnerability created by import dependence. For many critical minerals, a single nation or small group of nations controls the majority of global production. China dominates rare-earth mining and processing, accounting for roughly 70% of global mine production and about 90% of refining capacity [17]. The Democratic Republic of Congo produces approximately 70% of the world's cobalt, much of which flows through Chinese-owned processing facilities. Russia supplies substantial portions of global palladium and platinum-group elements while Turkey has emerged as a dominant source of boron. This geographical concentration creates multiple vulnerability points. Political instability in producing regions can disrupt supply chains. Deliberate export restrictions can be used as tools of geopolitical leverage as China demonstrated in 2010 when it temporarily restricted rare-earth exports during a diplomatic dispute with Japan, causing global prices to spike dramatically [18]. More recently, in 2023–2024, China imposed export-licensing requirements on gallium and germanium, materials essential to semiconductor and defense technologies, and later on certain graphite products, actions widely interpreted as targeted restrictions on U.S. and allied access to strategic inputs.

The vulnerability extends beyond raw-material extraction to encompass processing and refining capacity. Even when minerals are extracted in diverse locations, they often flow to a limited number of processing facilities that possess the specialized expertise and equipment necessary to produce high-purity materials suitable for advanced applications. China has systematically developed this midstream capacity over the past three decades, investing in separation technologies, refining infrastructure, and workforce development while Western nations allowed domestic capabilities to atrophy. The result is that even minerals mined in the United States or allied nations frequently must be shipped to China for processing before returning as usable materials or manufactured components. This processing bottleneck represents a strategic vulnerability that cannot be quickly remediated, as developing competitive separation and refining capacity requires substantial capital investment, specialized technical expertise, and years of operational optimization.

The COVID-19 pandemic and subsequent supply-chain disruptions provided a stark demonstration of the risks inherent in concentrated, geographically distant supply chains. Semiconductor shortages cascading from limited access to specialized materials halted automobile production lines and delayed consumer-electronics launches. Medical-equipment manufacturers struggled to source critical components. Defense contractors faced delays in procuring materials for weapons systems. These disruptions, while ultimately temporary, illustrated how quickly supply constraints can translate into economic losses and operational challenges. The experience catalyzed renewed attention to supply-chain resilience across both government and industry, creating political will for investments in domestic capacity that might have been economically marginal under normal market conditions.

1.3. Domestic Supply Strategies: The Role of Secondary Sources

Addressing U.S. critical-mineral supply vulnerability requires a multifaceted strategy encompassing new primary mining projects, international partnerships with aligned nations, enhanced recycling of end-of-life products, and recovery from unconventional or secondary sources. Each approach offers distinct advantages and faces particular challenges, and all must navigate complex permitting processes that can take multiple years; historically, the National Environmental Policy Act (NEPA) environmental impact statement (EIS) process alone has taken a median of roughly 4–5 years although the Fiscal Responsibility Act of 2023 now establishes presumptive timelines of 2 years for EISs and 1 year for EAs [7,19]. International partnerships can diversify supply sources and strengthen geopolitical alliances, but they introduce their own vulnerabilities related to political stability, transportation security, and alignment of economic interests. End-of-life recycling, which is crucial for circular-economy objectives and valuable for certain high-concentration applications like lithium-ion batteries, cannot meet the growing absolute demand for materials driven by advanced energy deployments and faces technical challenges in economically recovering dilute critical minerals from complex products.

Secondary sources, particularly mine tailings and waste rock from historical and active hardrock-mining operations, offer a complementary pathway that addresses several limitations of other approaches while creating unique opportunities. These materials already exist in concentrated locations with existing or historical industrial infrastructure: roads, power transmission, water access, and in some cases, partially operational processing facilities. The most energy-intensive step in mineral production, the initial excavation and comminution of ore, has already been completed. The regulatory and ownership landscape, while complex, is generally clearer than for undeveloped mineral prospects on federal land. Perhaps most significantly, recovery of critical minerals from mine tailings aligns environmental-remediation objectives with resource-security goals, creating a convergence of interests that can facilitate project approval and attract diverse funding sources from environmental-cleanup budgets as well as critical-mineral development programs.

The scale of the mine-tailings resource base is substantial. Over a century of intensive hardrock mining for copper, gold, silver, lead, zinc, uranium, and other commodities has generated billions of tons of tailings, distributed across thousands of sites in the western United States, with smaller concentrations in the Midwest and other regions. Historical mining operations focused on extracting the primary commodity of economic interest using available technology, typically discarding everything else as waste. Elements that were not economically valuable or technically recoverable at the time of original mining, but which have since become critical to modern technologies, remain in the tailings. Advances in analytical chemistry and characterization technologies now permit detailed assessment of these materials' critical-mineral content while innovations in hydrometallurgy, solvent extraction, and separation science enable recovery at concentrations that would have been technically or economically infeasible in past decades.

1.4. Scope and Purpose of this Report

This technical review and strategic assessment focuses exclusively on the potential for recovering critical minerals from mine tailings and waste rock generated by hardrock mining operations across the United States. The analysis encompasses tailings from diverse deposit types, including copper-gold porphyry systems, epithermal and orogenic gold deposits, sediment-hosted lead-zinc operations, uranium-mining districts, phosphate extraction, and other commodity-specific mining activities that have produced significant waste volumes with potential critical-mineral content. The report synthesizes available data on tailings locations, volumes, and composition; examines the technical approaches for mineral recovery; analyzes economic, regulatory, and social factors affecting project viability; and presents recommendations to accelerate responsible development of this domestic resource.

It is important to clearly delineate what this report does not address. Critical minerals can also be recovered from coal-combustion residuals, including fly ash and bottom ash, which contain elevated concentrations of REEs and other materials in certain geological settings. While coal-based resources represent a significant potential source of critical minerals and have been the subject of substantial DOE research and demonstration programs, they are explicitly excluded from this analysis. Separate assessments by other DOE teams are examining critical-mineral recovery potential from coal-based sources, and those analyses should be consulted for comprehensive understanding of that opportunity [20, 21].

The report is structured to provide both technical depth for subject-matter experts and strategic clarity for decision-makers. Following this introduction, Section 2 examines the current state of knowledge regarding critical minerals in mine tailings, including deposit-type-specific assessments and major site characterizations. Section 3 articulates the strategic benefits and rationale for pursuing tailings recovery, encompassing supply security, environmental remediation, economic development, and resource-efficiency dimensions. Section 4 provides a candid analysis of the barriers and challenges that must be addressed, from low mineral concentrations and technical complexity to regulatory hurdles and market risks. Section 5 surveys the current federal-policy landscape, including executive actions, legislative initiatives, and agency programs. Section 6 identifies critical knowledge gaps, with particular emphasis on the foundational need for comprehensive site characterization. Section 7 presents detailed recommendations across multiple domains. Section 9 offers concluding observations on a path forward and implementation priorities.

The intended audience encompasses senior leadership at the DOE, Department of War (DoW), Department of the Interior, Environmental Protection Agency (EPA) and other federal agencies with responsibilities for critical-mineral supply chains, as well as Congressional staff developing means to strengthen domestic mineral-production capacity. The goal is to provide decision-makers with the information necessary to make informed judgments about the role that mine-tailings recovery should play in national critical-mineral strategy and the specific actions that can most effectively enable this contribution.

2. CRITICAL MINERALS IN MINE TAILINGS

2.1. Mine Tailings as a Potential Resource

Mine tailings represent the finely ground rock and processing effluent that remain after target metals or minerals are extracted from mined ore. In typical hardrock mining operations, ore bodies contain the economically valuable commodity at concentrations ranging from less than one percent to perhaps a few percent by weight, with the remainder consisting of host rock and associated minerals. The mining and milling process involves crushing and grinding this material to liberate valuable minerals, followed by concentration through physical or chemical separation methods. The concentrated material proceeds to smelting or refining while the remaining material—typically 95 to 99% of the original ore volume—becomes tailings. These tailings were historically deposited in surface impoundments, valleys, or other containment structures where they remain as large accumulations of finely processed rock material.

For most of the history of mining in the United States, tailings were viewed purely as waste requiring disposal and management rather than as potential resources. Mining operations focused on maximizing recovery of the primary commodity using available technology and economic parameters, with little incentive to extract additional elements that lacked market value or technical recovery pathways. This approach was economically rational under historical conditions, but it resulted in the systematic discarding of elements that have since become critical to modern technology. The tailings from a copper porphyry operation, for example, contain not only residual copper that was technically or economically infeasible to recover completely, but also trace elements such as gallium, germanium, indium, and cobalt that occur naturally in these deposit types but were not targeted during original mining [3]. In some cases, historical tailings contain concentrations of certain critical minerals that are comparable to or higher than those found in some modern primary ores, reflecting higher cutoff grades and less-efficient processing technologies used at the time of original mining.

Several factors have transformed this historical waste into a potential resource. Advances in analytical chemistry and geochemical characterization now permit detailed, cost-effective analysis of tailings composition at trace-element concentrations that were difficult or impossible to measure reliably during much historical mining. Modern hydrometallurgical processes, including selective leaching, solvent extraction, and ion-exchange technologies, can economically recover metals at lower concentrations than were viable with older pyrometallurgical approaches. The economic value of critical minerals has increased substantially as demand has grown for electronic, nuclear energy, and defense applications. Perhaps most fundamentally, the tailings themselves exist in a physical form (already excavated, crushed, and in many cases partially concentrated through gravity or magnetic separation processes) that reduces the energy and cost barriers relative to processing virgin ore from new mining operations.

2.2. Current State of Knowledge: Available Data

Comprehensive characterization of mine tailings across the United States remains incomplete despite recent progress in data compilation and analysis. Collaborative efforts led by the DOE's national laboratories have assembled information from diverse sources, including the USGS, state geological surveys, the EPA, the Army Corps of Engineers, and mining-industry records. This compilation encompasses more than 300 distinct datasets sourced from over 100 different organizations and repositories, representing more than 10 gigabytes of digital information [3]. These datasets vary considerably in format, detail, spatial coverage, and vintage, ranging from recent geochemical surveys using modern analytical methods to historical mining records documented only in scanned paper reports.

The challenge extends beyond simple data availability to questions of data quality and immediate usability. Preliminary assessment indicates that fewer than one in ten existing datasets provides information sufficiently detailed and standardized to support project development and investment decisions without substantial additional processing [3]. Many valuable historical records exist only as scanned images of paper documents, requiring optical character recognition, manual transcription, or complete resurveying to convert into analyzable digital formats. Spatial data often lack precise georeferencing, with tailings locations described only by general vicinity or historical place names that may no longer appear on modern maps. Geochemical analyses from different time periods used varying analytical methods with different detection limits, making direct comparisons difficult. Some datasets provide detailed information on major commodity elements, but lack any trace-element analysis that would reveal critical-mineral content.

Geographic coverage of available data is highly uneven, reflecting both the historical distribution of mining activity and the priorities of different data-collection efforts. Major mining districts in Arizona, Nevada, Montana, and Idaho have received substantial attention from state geological surveys and federal agencies, resulting in relatively comprehensive documentation of at least the larger tailings sites. Other historically significant mining regions, particularly smaller districts or those dominated by operations that closed before modern environmental regulations required detailed site characterization, have much sparser data coverage. The situation is further complicated by the fact that many tailings sites lack any publicly available information regarding composition, volume, or even precise location. Private mining companies may possess proprietary data from historical operations, but this information rarely enters the public domain unless required by regulatory processes or voluntary disclosure.

2.3. Tailings at Legacy and Abandoned Mine Sites

Legacy and abandoned mine sites represent a significant fraction of the total mine-tailings inventory across the United States. These sites result from mining operations that ceased decades ago, often before modern environmental regulations required comprehensive closure planning, ongoing monitoring, or financial assurance for long-term stewardship. The Bureau of Land Management (BLM) estimates that hundreds of thousands of abandoned mine lands exist on federal property alone, with additional sites on state, tribal, and private lands [22]. While not all of these sites involve tailings—many are simply exploration pits or small-scale operations—thousands of locations include substantial tailings deposits, ranging from tens of thousands to millions of tons.

These legacy sites present both opportunities and challenges for critical-mineral recovery. The opportunities stem from several factors. Many legacy tailings sites represent ongoing environmental liabilities including acid mine drainage, heavy-metal leaching into groundwater or surface water, wind-blown dust dispersal, or the physical hazard of unstable impoundments. Projects that extract valuable minerals from these sites can simultaneously address environmental-remediation objectives, potentially accessing funding from Superfund appropriations, state cleanup programs, or other environmental-restoration budgets in addition to critical-mineral development resources. Legacy sites often exist in areas with historical mining infrastructure including roads, power transmission, and sometimes buildings or equipment that can be repurposed. Communities near these sites may welcome economic activity that provides employment and tax revenue, particularly in regions that have experienced economic decline since mine closures.

The challenges associated with tailings at legacy and abandoned mine sites are significant. The most-fundamental obstacle involves liability under federal and state environmental laws, particularly Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Under current legal interpretations, entities that disturb contaminated sites can potentially become responsible parties for all contamination at the location, even if they did not cause the original pollution and are attempting to improve conditions through cleanup and recovery activities [23]. This liability risk has a profound chilling effect on private-sector interest in legacy-site projects because the potential environmental remediation costs could far exceed any revenue from mineral recovery. Ownership and mineral-rights questions create additional complexity, with some sites having unclear title or disputes over whether mineral rights in tailings belong to surface owners, mineral estate holders, or potentially revert to the federal government under certain circumstances.

Technical challenges at legacy sites include the heterogeneity of tailings composition. Historical operations sometimes deposited tailings from different ore zones or time periods in distinct locations without detailed record-keeping, creating unknown variability in composition within a single site. Weathering and chemical alteration over decades can change the mineralogical character of tailings, potentially making them more or less amenable to processing, depending on the specific transformations that occurred. Some legacy sites have partially consolidated or developed surface vegetation, requiring decisions about whether disturbance for mineral recovery justifies disrupting achieved stabilization. Despite these challenges, the environmental co-benefits of legacy-site remediation, combined with mineral recovery, create a compelling case for developing policy mechanisms such as Good-Samaritan liability protections that could unlock this resource while improving environmental conditions.

2.4. Tailings at Active Mining Operations

Active mining operations present a distinctly different context for critical-mineral recovery relative to legacy sites. These operations maintain ongoing production of such primary commodities as copper, gold, or molybdenum, generating fresh tailings continuously that add to accumulated historical tailings from decades of operation at many sites. Active operations offer several significant advantages for critical-mineral recovery initiatives. The infrastructure, workforce, and technical expertise necessary for mineral processing already exist on site. Permitting and regulatory frameworks are established, with existing environmental-monitoring programs and compliance systems that can potentially be modified to accommodate additional processing rather than requiring entirely new approvals. The economic model allows for potential integration of critical-mineral recovery into existing operations, either as modifications to current processing circuits or as parallel operations that treat both fresh tailings and historical accumulations.

Active mine sites also benefit from better characterization than most legacy sites. Modern operations conduct detailed metallurgical testing, ore-body modeling, and tailings-composition monitoring as part of routine operations and regulatory compliance. This information can support evaluation of critical-mineral recovery potential with higher confidence and lower characterization costs than at abandoned sites. Companies operating active mines may have strong incentives to extract additional value from material that they are already processing, particularly if commodity prices for primary products are challenged or if critical-mineral recovery can improve overall project economics or extend mine life by making lower-grade primary ore economically viable to process.

Several initiatives demonstrate the feasibility of critical-mineral recovery at active operations. Rio Tinto’s Kennecott copper mine in Utah implemented a tellurium-recovery circuit (announced March 2021; production began May 2022) that extracts this critical semiconductor material from the copper-refining process [24]. The Stillwater Mine in Montana produces platinum and palladium as primary commodities while also recovering rhodium and other platinum-group elements. Phosphate operations in Idaho and Florida have explored REE recovery from processing waste streams although commercial implementation remains limited. These examples illustrate that integration of critical-mineral recovery into active operations is technically feasible and can create additional revenue streams that improve overall project economics.

However, active operations also face constraints that can limit critical-mineral recovery despite apparent technical feasibility. Primary production optimization remains the dominant consideration, and mining companies may be reluctant to implement processing changes that could disrupt established operations or risk primary-commodity recovery rates. Capital-allocation decisions prioritize investments that enhance primary production, and critical-mineral recovery circuits must compete with other potential uses of limited capital. Market uncertainty for critical minerals, which includes questions about long-term demand, price volatility, and the risk of foreign competitors undercutting prices to maintain market dominance, can make investment payback calculations unfavorable despite technical viability. Regulatory considerations also matter because modifications to operations may trigger new permitting requirements or public-review processes that companies prefer to avoid.

2.5. Critical-Mineral Content by Deposit Type

The critical-mineral content of mine tailings varies systematically by deposit type, reflecting the geological processes that formed the original ore bodies and concentrated specific element assemblages. Understanding these deposit-type-specific associations enables targeted assessment of tailings recovery potential and informs the development of processing strategies targeted for particular element combinations. Copper-gold porphyry deposits, which account for the largest individual tailings accumulations in the United States, exemplify this relationship. These deposits form when magmatic fluids rich in copper, gold, and associated trace elements interact with surrounding rock, creating extensive zones of mineralization. The resulting ore and associated tailings contain not only copper and gold, but also elevated concentrations of gallium, germanium, cobalt, and indium [3]. Arizona’s major porphyry systems, including Sierrita, Bagdad, and Morenci, have generated billions of tons of tailings with this characteristic trace-element signature.

Epithermal gold and silver deposits represent another significant deposit type with distinctive critical-mineral associations. These deposits form from relatively low-temperature hydrothermal fluids that transport gold and silver along with other elements through fracture systems in volcanic or sedimentary rocks. The tailings from epithermal systems in Nevada, Montana, and South Dakota contain indium as a notable critical-mineral byproduct [3]. The geological setting and mineralogical character of these deposits means that indium occurs in specific mineral phases that can potentially be targeted through selective processing. The large number of epithermal gold operations across the western United States and their substantial cumulative tailings inventory make this deposit type an important contributor to domestic critical-mineral potential.

Sediment-hosted lead-zinc deposits, particularly Mississippi Valley-type systems, provide another example of deposit-type-specific critical-mineral associations. These deposits form when metal-bearing fluids migrate through sedimentary basins and precipitate minerals in favorable geological structures. Missouri's Old Lead Belt represents a classic example in the United States, having produced vast quantities of lead and zinc over more than a century of mining. The tailings from these operations contain elevated gallium, germanium, neodymium, praseodymium, dysprosium, terbium, scandium, cobalt, and indium [3]. The presence of REEs in these systems reflects the geochemical affinity of these elements for the carbonate-dominated host rocks and the fluids that transported primary-ore metals. Missouri's St. Joe State Park hosts one of the largest individual lead-zinc tailings accumulations in the nation, with an estimated 122 MMT of material [3].

Uranium deposits constitute another important category, with several distinct subtypes that have generated tailings with varying critical-mineral associations. Roll-front uranium deposits in the Grants Mineral Belt of New Mexico and the Uravan Mineral Belt spanning Colorado and Utah were extensively mined during the Cold War era for nuclear-weapons programs. These deposits formed when uranium-bearing groundwater encountered reducing conditions in sandstone formations, precipitating uranium minerals along with vanadium, selenium, and molybdenum [5]. The tailings from these operations contain residual concentrations of these associated elements, with vanadium being particularly significant given its applications in high-strength steel alloys and emerging grid-scale energy-storage technologies. Historical mining in these districts generated substantial tailings volumes that remain in various stages of remediation under federal and state oversight.

Phosphate-mining operations in Idaho, Florida, North Carolina, and Utah produce tailings and processing residuals with distinct critical-mineral signatures. Phosphate ore, which is processed to produce phosphoric acid for agricultural fertilizers, contains elevated concentrations of REEs, uranium, and thorium that move into processing waste streams, including phosphogypsum [25]. The rare-earth content in phosphate systems reflects the geochemical similarity between phosphorus and the REEs that allows rare earths to substitute into apatite mineral structures. Florida's phosphate operations alone have generated billions of tons of phosphogypsum stockpiles that contain recoverable rare-earth concentrations. The radioactivity associated with uranium and thorium content creates additional regulatory considerations, but also presents an opportunity to address existing radiological concerns while recovering valuable materials. By extracting uranium and thorium alongside rare earths, tailings-recovery processes have the potential to generate materials relevant to the nuclear fuel cycle and simultaneously lower the radiological content of phosphogypsum, creating pathways for its safe reuse as a soil amendment in regions where regulatory thresholds can be met.

Iron-oxide-apatite and iron-oxide-copper-gold deposits represent a less-common, but locally significant, deposit type with elevated REE and fluorine content. The Pea Ridge mine in Missouri, which operated primarily for iron-ore production, left tailings containing significant rare-earth-bearing apatite along with fluorite [26]. Similar systems occur in other locations, including Arizona and Idaho. The apatite in these systems serves as the principal host for REEs, and the presence of discrete apatite mineral grains, rather than disseminated trace-element concentrations, may enable concentration through physical-separation methods before chemical processing.

Carbonatite deposits and associated alkaline igneous intrusions represent highly specialized deposit types that are relatively uncommon, but can contain exceptional concentrations of REEs, niobium, and other critical materials. These deposits form from unusual magmatic systems enriched in carbonate and alkaline components. The Mountain Pass deposit in California, the only currently operating rare-earth mine in the United States, exemplifies this deposit type. While carbonatites have generated less tailings volume than the major base and precious-metal deposit types, their distinctive geochemistry and high critical-mineral grades make them important targets for both primary development and potential tailings recovery where historical operations occurred. These systems often contain elevated uranium and thorium associated with rare-earth minerals, particularly monazite, requiring careful management of naturally occurring radioactive materials. In settings where monazite- and bastnäsite-rich tailings or ores contain appreciable uranium and thorium, recovering these actinides can contribute feedstock for nuclear-fuel–cycle applications while simultaneously reducing the radiological inventory requiring long-term management.

2.6. Major U.S. Tailings Sites: Examples and Scale

Recent data-compilation efforts have enabled preliminary quantification of the largest tailings accumulations in the United States and their critical-mineral content. Analysis of readily accessible data indicates that the ten largest deposit-type categories account for approximately 13,904 MMT of tailings across 189 distinct piles in multiple states [3]. Copper-gold porphyry systems dominate this inventory, with an estimated 8,507 MMT distributed across 53 sites, primarily in Arizona, California, New Mexico, and South Carolina. Across California, Montana, Nevada, South Carolina, and South Dakota, epithermal and orogenic gold deposits together contribute approximately 2,449 MMT from 51 sites. Sediment-hosted lead-zinc systems account for 1,123 MMT at 36 locations spanning Alaska, Arizona, Colorado, Michigan, Missouri, Montana, New Mexico, Nevada, Tennessee, Texas, and Utah. Molybdenum porphyry deposits contribute 953 MMT from eight sites in Colorado and New Mexico.

Individual sites demonstrate the enormous scale of tailings accumulations at major mining operations. The Sierrita copper mine in Arizona hosts the single largest identified tailings pile in the United States with an estimated 2,893 MMT, equivalent to approximately 38.3 billion cubic feet of material [3]. This massive accumulation results from decades of operation processing porphyry copper ore and contains residual copper along with gallium, germanium, cobalt, and indium characteristic of this deposit type. The Bagdad copper mine, also in Arizona, has generated approximately 740 MMT of tailings while the Morenci operation accounts for 635 MMT. These Arizona porphyry systems collectively represent billions of tons of tailings with relatively consistent mineralogical characteristics that could potentially support large-scale critical-mineral recovery operations.

Gold-mining operations have produced several of the largest individual tailings sites. The North Block tailings impoundment in Nevada contains an estimated 515 MMT of material from epithermal gold-mining operations, with indium as the principal critical-mineral byproduct. The Fort Knox gold mine in Alaska has accumulated approximately 507 MMT of tailings containing germanium, cobalt, and indium. The Barrick Goldstrike tailings-storage facility in Nevada holds an estimated 103 MMT. These large gold-associated tailings sites reflect the combination of relatively low gold grades in most ore bodies, requiring processing of vast tonnages of rock to produce economic gold quantities, and the long operational life of major gold mines that have processed millions of tons of ore annually for decades.

Molybdenum production has generated exceptionally large tailings accumulations at specific locations, despite molybdenum being less-widely mined than copper or gold. The Climax mine in Colorado, which operated intermittently as the world’s largest molybdenum producer, left approximately 409 MMT of tailings containing germanium and indium, along with residual molybdenum [3]. The massive scale of tailings at this single site reflects both the low molybdenum grades in the ore body, typically less than 0.3%, and the decades of high-volume production that made Climax economically viable despite these low concentrations.

Historical base-metal mining operations have created significant tailings accumulations with complex critical-mineral assemblages. The St. Joe State Park tailings dam in Missouri, a legacy of lead mining in the Old Lead Belt, contains an estimated 122 MMT of material with gallium, germanium, neodymium, praseodymium, dysprosium, terbium, scandium, cobalt, and indium [3]. The Red Dog zinc mine in Alaska, one of the world's largest zinc producers, has accumulated approximately 121 MMT of tailings with similar critical-mineral associations. These multielement tailings present both opportunities through the potential to recover multiple valuable products, and challenges through the technical complexity of achieving selective separation.

2.7. Extraction Technologies and Recovery Methods

The fundamental technologies for recovering critical minerals from mine tailings build upon established mineral-processing and extractive-metallurgy methods that have been refined over decades for treatment of primary ores. The adaptation of these technologies to tailings processing involves modifications to account for the specific characteristics of tailings materials, including their fine particle size, partial oxidation from atmospheric exposure, and the typically lower concentrations of target elements compared to primary ores. The general processing sequence begins with characterization and sampling to understand the mineralogical associations and elemental distributions within the tailings mass, followed by physical beneficiation steps that may concentrate target minerals, chemical leaching to dissolve metals into solution, separation and purification to isolate specific elements, and finally, precipitation or electrowinning to produce salable products (Figure 1).

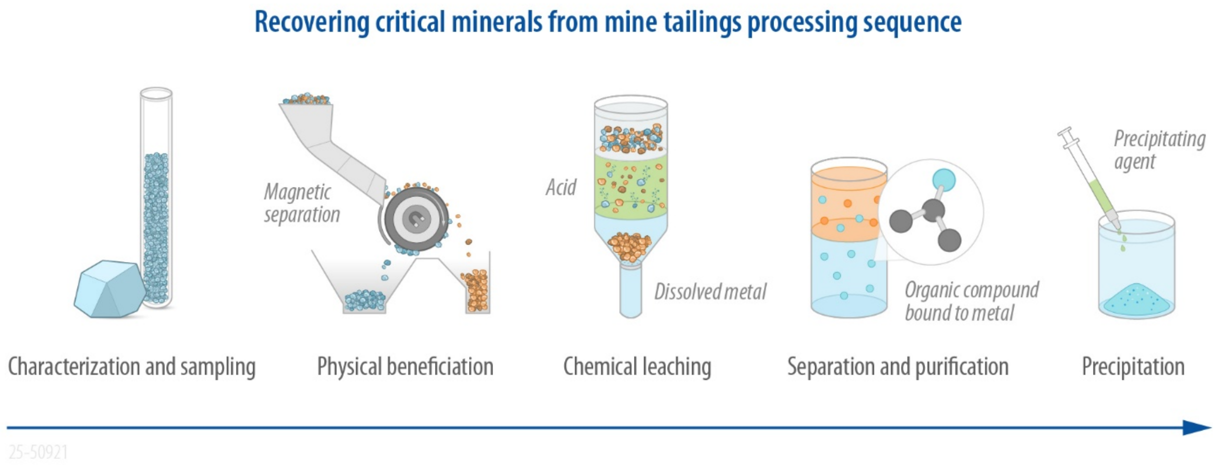

Figure 1. The sequence of recovering critical minerals from mine tailings.

Physical-beneficiation methods can potentially upgrade critical-mineral concentrations before chemical processing, reducing the volume of material requiring energy-intensive leaching and separation. Gravity separation techniques exploit density differences between minerals, potentially concentrating heavy minerals that host materials such as rare earths or platinum-group elements. Magnetic separation can recover minerals with magnetic-susceptibility differences, which may be relevant for certain rare-earth minerals or cobalt-bearing phases. Froth flotation, the dominant concentration method in base- and precious-metal processing, can selectively float or depress specific mineral phases based on their surface chemistry. However, the effectiveness of physical beneficiation is highly dependent on the mineralogical character of the tailings, particularly whether target elements occur in discrete mineral grains amenable to physical separation or are disseminated in fine particles or solid solution in major minerals.

Chemical leaching represents the most-versatile approach for extracting metals from tailings and is often essential when physical methods cannot achieve sufficient concentration. Acid leaching using sulfuric, hydrochloric, or nitric acid can dissolve many metals from oxide, sulfide, or mixed mineralogies. The choice of lixiviant depends on the specific mineralogy, the selectivity required to avoid excessive dissolution of unwanted elements, and economic factors, including reagent costs and the challenges of managing spent leach solutions. Alkaline leaching using sodium-hydroxide or sodium-carbonate solutions provides an alternative approach for certain minerals and can offer advantages in managing environmental impacts or achieving selective dissolution. Biological leaching, which employs microorganisms to facilitate metal dissolution, represents an emerging technology that shows promise for treating certain tailings types with potentially lower energy requirements and reduced reagent consumption compared to conventional chemical leaching [27].

Once metals are dissolved into leach solutions, separation and purification technologies must isolate individual elements or element groups from complex mixtures that may contain dozens of dissolved species. Solvent extraction, also known as liquid-liquid extraction, uses organic compounds that selectively bind target metals and transfer them from aqueous leach solutions into an organic phase from which they can be stripped back into a purified aqueous solution. This technology forms the foundation of REE separation, where carefully designed solvent-extraction circuits can separate individual rare earths from complex mixtures through multistage cascades [28]. For example, INL has developed advanced separation-science capabilities specifically targeting critical-mineral recovery, including novel extractants and process configurations that can improve separation efficiency and reduce reagent consumption.

Ion exchange and adsorption processes provide complementary separation mechanisms particularly useful for treating dilute solutions or achieving high-purity products. Functionalized resins or adsorbent materials can selectively capture target metals from solution, allow impurities to wash through, and then release concentrated target metals through elution with appropriate reagents. Membrane-based separation technologies such as electrodialysis, nanofiltration, and selective membranes represent emerging approaches that may offer advantages for certain applications, particularly in reducing energy consumption or improving selectivity. Precipitation methods convert dissolved metals into solid products through pH adjustment, addition of precipitating agents, or electrochemical reduction, providing the final step in many recovery flowsheets.

The integration of these unit operations into complete processing flowsheets requires careful optimization based on the specific tailing composition, target products, and economic constraints. Pilot-scale testing, using representative tailings samples, is typically essential to demonstrate technical feasibility, optimize reagent consumption and recovery efficiency, and generate design parameters for commercial-scale facilities. Several federally supported pilot projects have demonstrated critical-mineral recovery from mine tailings. For example, a project in Missouri operated by U.S. Strategic Metals (Missouri Cobalt) at the Madison Mine near Fredericktown has reprocessed historic lead-zinc tailings to recover cobalt, nickel, and copper while capping the residual tailings in engineered impoundments to reduce environmental contamination [29,30]. Research efforts at multiple national laboratories and universities have developed and tested flowsheets for rare-earth recovery from various tailings types, establishing proof-of-concept for technologies that could be scaled to commercial implementation with appropriate investments and policy support.

3. BENEFITS AND STRATEGIC RATIONALE

3.1. Supply Security and Economic Resilience

The recovery of critical minerals from domestic mine tailings directly addresses the most-fundamental strategic challenge facing U.S. critical-mineral supply chains: the vulnerability created by concentrated dependence on geopolitically unreliable foreign sources. Every ton of REEs, cobalt, gallium, or other critical materials produced from domestic tailings represents a corresponding reduction in import requirements and the associated exposure to supply disruptions, price manipulation, or deliberate export restrictions. This supply-diversification benefit operates at multiple scales. At the national level, domestic production from tailings contributes to overall supply security by providing sources that cannot be interdicted by hostile actors or affected by political instability in distant regions. The materials produced domestically remain available regardless of trade tensions, sanctions to certain regimes, or military conflicts that might disrupt international commodity flows.

The concept of supply-chain resilience extends beyond simple geographic diversification to encompass the ability to respond rapidly to changing conditions. Traditional primary mining projects require extensive lead times, often many years from discovery through permitting to production; historically, the NEPA EIS component alone has taken a median ~4–5 years, with the Fiscal Responsibility Act of 2023 setting presumptive 2-year EIS and 1-year EA limits [7,19] Tailings-recovery operations can potentially be deployed more rapidly because the material already exists in accessible locations with some level of existing infrastructure. While establishing full-scale processing facilities still requires substantial time and investment, the elimination of exploration risk and reduction in permitting complexity for sites that are already permitted for mining operations or remediation projects can compress development timelines. This responsiveness enhances national capacity to adapt to evolving technological demands or strategic priorities without accepting multidecade dependencies on foreign suppliers.

Economic resilience complements supply security by reducing the vulnerability of domestic industries to price volatility in critical-mineral markets. The concentrated nature of global production for many critical minerals creates conditions where relatively small supply disruptions or demand changes can cause dramatic price swings. The rare-earth price crisis of 2010–2011, when Chinese export restrictions caused some rare-earth oxide prices to increase by more than 1000% in a matter of months, demonstrated how quickly market conditions can deteriorate [31]. Industries dependent on these materials face difficult choices during such crises: absorb cost increases that eliminate profit margins, attempt to substitute alternative materials that may compromise performance, or curtail production while awaiting price stabilization. Domestic production from tailings provides price stability by ensuring that some fraction of supply responds to market signals within the United States rather than reflecting the strategic calculations of foreign governments or the market power of dominant foreign producers.

The companionality phenomenon documented in research by Nassar and colleagues adds another dimension to supply-security considerations. Their analysis demonstrated that 61% of evaluated metals are obtained primarily as byproducts of other host metals, rather than through dedicated mining operations [8]. This means that the supply of many critical minerals depends not on demand for those minerals themselves; rather, it depends on the economics and production levels of host metals. When host-metal production declines due to low prices or mine closures, companion-metal supplies contract regardless of companion-metal demand or prices. Tailings recovery offers a pathway to break this linkage by targeting critical minerals directly, rather than depending on the byproduct relationship. A processing facility specifically designed to recover REEs or cobalt from tailings can respond to demand for those materials without being constrained by the economics of copper or lead-zinc production that drive conventional companionality relationships.

3.2. Environmental Remediation Co-Benefits

Mine tailings represent significant environmental liabilities across the United States, with thousands of sites posing ongoing risks to water and air quality and ecosystem health [32]. The conversion of these liabilities into resources through critical-mineral recovery creates a rare convergence of environmental and economic objectives. Many tailings contain sulfide minerals that oxidize upon exposure to air and water, generating sulfuric acid through a process known as acid mine drainage. This acidic water mobilizes heavy metals, including copper, lead, zinc, cadmium, and arsenic, which then flow into streams and rivers, devastating aquatic ecosystems and potentially contaminating drinking-water sources. The persistence of acid mine drainage can extend for decades or centuries after mining operations cease, requiring expensive ongoing treatment to prevent environmental damage [33].

Reprocessing operations that extract critical minerals from tailings inherently disturb and rehandle the material, providing an opportunity to fundamentally alter its environmental behavior. Modern processing approaches can neutralize acid-generating potential through chemical treatment, separate and stabilize metal-bearing phases, and place the processed residual material in engineered containment facilities with proper liners, covers, and drainage controls that prevent environmental releases. The Missouri lead-zinc tailings reprocessing project exemplifies this co-benefit approach. The operation recovered cobalt, nickel, and copper from legacy tailings while transferring the processed residual material into lined impoundments with leachate collection systems, dramatically reducing metal loading to surrounding water bodies [1]. The environmental improvement achieved through this project secured support from state environmental agencies and local communities that might otherwise have opposed industrial activity at the site.

Wind erosion of fine-grained tailings creates another environmental pathway that reprocessing can address. Unmanaged tailings piles, particularly in arid western states, can generate dust that disperses metal-contaminated particulates across surrounding landscapes. This dust can contaminate soils, vegetation, and surface-water bodies at considerable distances from the source. Human exposure through inhalation or ingestion of contaminated dust creates potential health risks, particularly for communities located near large tailings sites. Processing operations that consolidate tailings, add moisture for dust control during handling, and ultimately place residual material under engineered covers eliminate this dispersal pathway. The reduction in dust generation and associated metal transport represents a measurable environmental improvement that benefits both ecological and human health.

The structural stability of tailings impoundments constitutes another critical environmental consideration. Tailings-dam failures, while relatively rare, have caused catastrophic environmental damage and loss of life when they occur. The sudden release of millions of tons of liquefied tailings can devastate downstream communities and ecosystems, as demonstrated by major failures in other countries that killed hundreds of people and caused billions of dollars in damages. The United States has experienced smaller-scale tailings releases that, while not resulting in mass casualties, caused severe environmental damage and remediation costs. Reprocessing operations that remove tailings material from potentially unstable impoundments and either process it completely or relocate it to modern, engineered facilities designed to current safety standards reduce the ongoing risk of catastrophic failure. This risk reduction has particular value for sites located upstream of populated areas or critical infrastructure.

3.3. Economic Development and Job Creation

Many regions that host significant mine-tailings accumulations have experienced economic decline following mine closures, creating communities with available workforce, existing industrial infrastructure, and strong motivation to identify new economic opportunities. The development of critical-mineral recovery operations in these locations can provide economic revitalization through multiple mechanisms. Direct employment in tailings processing includes positions in operations, maintenance, engineering, environmental monitoring, and management that can use skills from the existing workforce, particularly former mining employees whose technical knowledge and work culture align well with mineral-processing operations. The specialized nature of critical-mineral separation and refining also creates opportunities for higher-skilled technical positions, including process metallurgists, analytical chemists, and automation specialists that offer career-advancement pathways and attract educated workers to rural communities.

The economic-multiplier effects of mining and mineral-processing operations amplify the direct employment benefits. Processing facilities require supplies, services, and support from local and regional businesses: equipment suppliers, maintenance contractors, analytical laboratories, transportation services, and professional services. Employees spend wages on housing, retail goods, restaurants, and services within their communities, supporting additional employment in those sectors. Local and state governments collect tax revenues from property, sales, and potentially production that can fund public services and infrastructure improvements. Economic-impact analyses of similar industrial operations typically estimate that each direct job in mineral processing supports two to three additional indirect and induced jobs in the regional economy [34,35].

The infrastructure legacy of historical mining provides economic advantages for new tailings-recovery operations. Many mining districts retain roads, electrical transmission, water-supply systems, and rail access that were constructed to support previous mining activity. These infrastructure assets, which represent millions or tens of millions of dollars of embedded investment, can be employed by new operations at much-lower cost than constructing equivalent infrastructure in undeveloped locations. Some sites retain buildings, settling ponds, or other physical assets that can be repurposed. The existence of communities with housing, schools, medical facilities, and other amenities also reduces the infrastructure investment required relative to remote greenfield developments that must create completely new communities.

Community-benefit agreements have emerged as a mechanism to ensure that local populations share in the economic value generated by resource-extraction and processing operations. These agreements, negotiated between project developers and community representatives, can include commitments to local hiring preferences, funding for community infrastructure or services, revenue-sharing arrangements, or support for economic-diversification initiatives. In the context of tailings-recovery operations that provide environmental remediation co-benefits, community-benefit agreements can help build social license by demonstrating tangible local benefits while addressing legitimate community concerns about the impacts of industrial activity. The enhanced community support that results from well-designed benefit agreements can facilitate permitting processes and reduce the risk of opposition that might delay or prevent project implementation. For example, Lithium Americas’ 2022 Community Benefits Agreement with the Fort McDermitt Paiute and Shoshone Tribe for the Thacker Pass lithium project includes commitments to local hiring, workforce training, community investment, and collaborative environmental stewardship—demonstrating how well-structured benefit agreements can strengthen social license and improve project-permitting outcomes [36].

3.4. Lower Cost and Energy Relative to Primary Mining

The economics of mineral recovery from tailings benefit from the elimination of several major cost categories that dominate primary mining operations. Exploration costs, which can consume tens of millions of dollars during the search for economic ore deposits, are eliminated entirely because the tailings material already exists in known locations with at least preliminary characterization. Mining costs, including the capital investment in equipment for drilling, blasting, loading, and hauling, as well as the ongoing operational costs of rock excavation, constitute 40–60% of total costs in typical hardrock mining operations [37]. Tailings processing begins with material already at the surface in relatively accessible locations, avoiding these substantial mining-related expenditures.

Comminution (the crushing and grinding of ore to liberate valuable minerals) represents one of the most energy-intensive steps in mineral processing, typically consuming more electrical energy than all other processing steps combined. The fine particle size of tailings, which results from the original milling of ore, means that much of this energy-intensive size reduction has already been accomplished. While some tailings applications may require additional grinding to achieve optimal liberation of target minerals or to expose fresh mineral surfaces for leaching, the energy requirement is substantially less than processing virgin ore from primary mining [38]. This energy advantage translates directly to reduced operating costs per ton of critical mineral produced, supporting both economic and environmental objectives.

The existing permits, environmental baseline data, and regulatory relationships at many tailings sites, particularly those at active mining operations or sites already undergoing remediation, reduce permitting timelines and associated costs relative to new mining projects. While tailings-processing projects still require appropriate regulatory review and permitting, the scope of environmental analysis may be reduced when projects are located at previously disturbed sites or integrate with ongoing remediation activities. The ability to leverage existing NEPA documentation, water-discharge and air-quality permits, and other regulatory approvals can compress the regulatory pathway and reduce the legal, consulting, and administrative costs that mining companies identify as major barriers to new project development in the United States.

However, the cost advantages of tailings processing face countervailing factors that require careful site-by-site evaluation. Critical-mineral concentrations in tailings vary widely depending on when mining occurred and what technologies were available. Some historical tailings contain higher concentrations than modern primary ores because decades-old extraction methods required higher cutoff grades to be economic, meaning material that was discarded as “waste” in 1950 may exceed the grade of ore currently being mined with modern technology. Conversely, other tailings contain only trace concentrations of elements that were not valued or detectable during original operations. This heterogeneity means that grade comparisons cannot support blanket assertions about economic competitiveness.

What remains consistent is that primary mining operations face downstream challenges of infrastructure development, complex processing, and residual-waste management, while also bearing substantial upstream costs that tailings recovery avoids entirely: exploration expenditures averaging tens of millions of dollars, mining operations constituting 40–60% of total project costs, and energy-intensive comminution representing the single largest power consumer in mineral processing. For tailings with comparable or higher grades than primary ores, the elimination of these upstream costs creates clear economic advantage. For lower-grade tailings, the cost structure becomes more complex, requiring detailed analysis of whether avoided mining and comminution costs offset the need to process larger volumes. Each potential tailings-recovery project requires site-specific economic analysis accounting for material characteristics, target-mineral concentrations, processing requirements, infrastructure availability, and regulatory context.

3.5. Resource Efficiency and Circular Economy

The recovery of critical minerals from mine tailings exemplifies the principle of a circular economy: maximizing resource utilization by capturing value from materials that were previously treated as waste. From a systems perspective, the complete extraction of all potentially valuable elements from ore bodies represents optimal resource stewardship, ensuring that the disruption and environmental impacts associated with mining generate maximum societal benefit. Historical mining operations, constrained by technology and economics, extracted only the most-valuable and easily recovered commodities, effectively mining ore bodies once, but capturing perhaps 20–40% of the total potential value. Modern tailings recovery enables a second extraction that approaches more-complete resource utilization, without the full environmental footprint of new mining operations.

This approach aligns with evolving perspectives on mineral-resource management that emphasize resource efficiency and waste minimization. The European Union’s circular-economy action plan, and similar initiatives in other jurisdictions, increasingly recognize that waste streams from one industrial process can serve as feedstocks for other processes, reducing primary resource extraction and the associated environmental impacts [1]. Mine-tailings recovery fits naturally within this framework by converting what was previously an environmental liability requiring perpetual management into a productive resource. The transformation also improves the overall resource efficiency of the original mining operation retrospectively, allowing society to capture value from historical extraction that would otherwise remain unrealized.

The concept of “urban mining,” which refers to recovering valuable materials from anthropogenic accumulations rather than from virgin geological resources, encompasses tailings recovery, electronic waste recycling, building-material recovery, and other secondary-source exploitation. Urban mining offers advantages in terms of energy efficiency, environmental-impact reduction, and resource security relative to traditional extractive industries. Tailings represent one of the largest and most-accessible urban-mining opportunities, with material already concentrated in specific locations, partially processed, and in some cases well-characterized. The development of economically viable tailings-recovery technologies and business models can establish proof-of-concept and infrastructure that enables broader urban-mining initiatives, creating demonstration effects that encourage similar approaches for other material flows.

The finite nature of high-grade mineral deposits provides long-term strategic justification for pursuing tailings recovery and other secondary sources. Because the highest-grade, most-accessible ore deposits are depleted through mining, future primary production must increasingly target lower-grade resources that require the processing of larger volumes of material to produce equivalent product quantities. This grade-decline trajectory is evident across many commodities, with average ore grades for copper, gold, and other metals having decreased substantially over recent decades as mines have depleted the richest zones and expanded to lower-grade material. Tailings recovery, electronic-waste recycling, and other secondary sources can moderate the pace of grade decline in primary resources by supplementing supply and reducing pressure to exploit marginal deposits. This moderation extends the economic life of higher-grade primary resources and provides time for technology development that may enable future extraction of very low-grade resources that are currently not economical.

The integration of tailings recovery into domestic critical-mineral supply chains also supports the development of processing expertise and infrastructure that strengthen overall industrial capacity. The separation science, analytical chemistry, process and chemical engineering, and metallurgical capabilities required for efficient tailings processing are directly applicable to primary-ore processing, electronic-waste recycling, and manufacturing of products containing critical minerals. Investment in tailings-recovery operations thereby builds technical capabilities with value extending beyond the specific projects, creating a knowledge base and workforce that enhances national competitiveness across multiple industries. For example, INL’s expertise in separation science and advanced materials characterization, developed through diverse research programs, including spent-nuclear-fuel processing, has found direct application in critical-mineral recovery, illustrating how capabilities developed in one context can enable solutions in seemingly unrelated domains [39].

4. CHALLENGES AND BARRIERS

4.1. Low Concentrations and Scale Requirements

The fundamental challenge facing critical-mineral recovery from mine tailings stems from the inherently low concentrations of target elements in the material. By definition, tailings represent what remained after conventional mining operations extracted the primary commodities using economically optimized processes. The critical minerals now targeted for recovery exist at trace concentrations, often measured in parts per million rather than the percent-level grades typical of primary ores. A copper-porphyry tailings pile might contain 50–200 parts per million of gallium or germanium, compared to primary ores for these elements that would typically grade at several hundred to over a thousand parts per million [53]. This concentration differential means that vastly larger volumes of tailings must be processed to produce equivalent product quantities than is seen in primary mining operations.

The volumetric scale requirement creates cascading implications for project design and economics. Processing facilities must handle throughputs measured in thousands or tens of thousands of tons per day to generate sufficient critical-mineral production to justify capital investment and operating costs. These large-scale operations require substantial processing equipment, including grinding mills if additional size reduction is necessary, leaching reactors capable of managing enormous volumes of slurry, and separation circuits with the capacity to treat the resulting solutions. The capital investment for such facilities can easily reach hundreds of millions of dollars, creating a high barrier to entry that limits the number of potential project developers and demands careful economic analysis to justify expenditure [3].

Material-handling logistics present practical challenges that increase with scale. Moving thousands of tons of tailings daily from storage locations to processing facilities requires substantial earthmoving equipment, conveyor systems, or slurry pipelines. The processed residual material, which typically constitutes 95% or more of the input mass after critical-mineral extraction, must be deposited in engineered storage facilities designed to modern environmental standards. The construction and operation of these residual-storage facilities add costs and requires the securing of appropriate sites with adequate capacity, proper foundation conditions, and acceptable environmental characteristics. The sheer physical scale of the operation creates visibility that can attract scrutiny from regulatory agencies and public-interest groups, potentially complicating permitting even for projects with strong environmental credentials.

4.2. Multi-Element Separation and Product Portfolio Complexity

Mine tailings typically contain multiple critical minerals, rather than a single target element, reflecting the geological processes that concentrated diverse element assemblages in the original ore bodies. While this multi-element character creates opportunities to generate multiple revenue streams that improve overall project economics, it also introduces technical complexity in achieving selective separation. A lead-zinc tailings pile, for example, might contain economically interesting concentrations of cobalt, nickel, germanium, and REEs, all in the same material [6]. Recovering these elements requires processing steps that can selectively separate chemically similar metals from complex mixtures containing dozens of dissolved species.

The chemical similarity of some critical-mineral groups exacerbates separation challenges. REEs, for instance, exhibit nearly identical chemical behavior due to their similar electronic structures, making separation into individual high-purity elements technically demanding and expensive. Conventional rare-earth separation requires solvent extraction cascades with dozens or even hundreds of stages to achieve the purity specifications required for magnet manufacturing, phosphors, or other high-value applications [3]. The capital and operating costs of these separation systems represent major components of overall rare-earth production costs. Similar challenges affect platinum-group element separation, where elements such as platinum, palladium, rhodium, and iridium must be separated despite similar chemistries.

Product-specification requirements add another layer of complexity. End users of critical minerals, particularly in electronics and advanced materials applications, often demand extremely high purity, with strict limits on specific contaminants. Semiconductor applications might require gallium or germanium with purity exceeding 99.999%, with particular attention to elements that can affect semiconductor properties even at parts-per-billion concentrations. Magnet manufacturers need rare-earth oxides meeting purity specifications that vary by element and application. Achieving these stringent purity requirements from complex tailings matrices may require multiple processing stages, driving up costs and creating technical risk that the desired specifications cannot be met economically.

While site-specific economics vary widely, available pilot-scale results and early commercial experience indicate that costs associated with critical-mineral recovery from tailings are dominated by separation and purification rather than material handling or mining. Order-of-magnitude estimates reported in the literature and industry disclosures suggest that processing and separation costs commonly fall in the range of tens to several hundreds of dollars per ton of tailings processed, with capital requirements for separation facilities frequently reaching tens to several hundreds of millions of dollars depending on throughput, mineral suite, and product-purity requirements. These costs are driven primarily by reagent consumption, energy intensity, and the need for multi-stage separations to isolate chemically similar elements from complex matrices. At current technology readiness levels, these separation-related costs often exceed the value of recovered materials, particularly for low-grade or multi-element tailings, making them a central economic barrier, independent of site characterization or resource scale.

The market dynamics for different critical minerals complicate product-portfolio planning. Some critical minerals have well-established markets with multiple buyers and transparent pricing while others face thin markets with limited numbers of potential customers and opaque pricing mechanisms. The quantities of different elements recovered from tailings may not align with market-demand ratios, potentially creating surpluses of some elements while other elements remain in short supply. This mismatch can affect project economics if certain elements must be stockpiled or sold at discounted prices due to limited demand, reducing the revenue contribution from those elements below the levels assumed in initial feasibility assessments.

4.3. Technical Complexity and Product Quality

The weathering and chemical alteration that tailings undergo during decades of surface storage can significantly change their mineralogical character compared to fresh ore. Sulfide minerals oxidize to form sulfates, oxides, and hydroxides through interaction with atmospheric oxygen and water. These secondary minerals may exhibit different behavior in processing than do the primary minerals that existed in the original ore, potentially requiring modified leaching conditions, different reagents, or alternative processing approaches. The degree of weathering varies both between different tailings sites and within individual sites based on factors including climate, drainage conditions, and the length of time since deposition. This heterogeneity complicates process design and can lead to variable recovery performance if not adequately characterized and managed.

The fine particle size of tailings, while it eliminates the need for energy-intensive grinding, can create processing challenges in other respects. Very-fine particles can be difficult to separate from liquid in solid-liquid separation equipment, leading to inefficient thickening and filtration that increases water consumption and creates very wet filter cakes that are expensive to manage. Fine particles also present larger surface areas for chemical reactions, which can increase reagent consumption if undesired reactions with gangue minerals[a] compete with the desired extraction of target metals. The control of solution chemistry in these high-surface-area systems requires careful attention to pH, redox potential, and reagent

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[a] A gangue mineral is the non-economic minerals or rock that occurs with the ore mineral of interest.

concentrations to optimize selective dissolution of target minerals while minimizing dissolution of unwanted components.

Scaling from laboratory or pilot testing to commercial production presents risks that are inherent to any metallurgical process development but can be particularly acute for tailings applications. Bench-scale tests using a few kilograms or tens of kilograms of carefully selected tailings samples may not adequately represent the variability and complexity that will be encountered when processing thousands of tons daily from heterogeneous tailings deposits. Phenomena such as equipment fouling, reagent degradation, or trace-element interferences that do not appear at small scale can become significant problems at commercial scale. Conservative engineering design to accommodate these uncertainties adds cost while aggressive optimization based on limited data creates risk of operational difficulties that can jeopardize project economics [28].

4.4. Regulatory and Permitting Hurdles

The permitting pathway for mine-tailings reprocessing projects intersects multiple regulatory frameworks in ways that create complexity and uncertainty. Projects may be classified as mining operations, waste-management facilities, remediation activities, or some hybrid category depending on specific site characteristics and regulatory jurisdiction. This ambiguity can result in conflicting interpretations of which regulations apply, which agencies have jurisdiction, and what approval processes are required. The lack of established precedents for large-scale critical mineral recovery from tailings means that regulatory agencies cannot simply apply templates from previous, similar projects but must instead develop approaches that fit unique circumstances, extending timelines and creating unpredictability.

The NEPA review process, required for projects on federal lands or requiring federal permits, can consume years, even for well-designed projects that pose minimal environmental risk. The preparation of EISs involves extensive data collection, analysis of alternatives, assessment of potential impacts across multiple resource areas, and opportunities for public comment and agency review. While recent reforms have imposed page limits and presumptive time limits on NEPA documents, the practical implementation of these reforms remains to be demonstrated for complex mining-related projects. The prospect of litigation challenging NEPA adequacy creates additional uncertainty as even favorable agency decisions can be delayed or reversed through judicial review [19].

State-level permitting requirements add layers of review that must be navigated in parallel with federal processes. Water-discharge permits under the Clean Water Act, air-quality permits for emissions from processing operations, waste-management permits for disposal of processed residual tailings, and various other approvals involve separate application processes, technical studies, and review periods. The coordination among different permitting agencies is often imperfect, with approvals from one agency potentially contingent on decisions from other agencies in ways that create sequential delays. Some states have developed streamlined processes for mining-related permits that provide coordinated review and firm timelines, but implementation varies considerably based on political priorities and agency resources.

4.5. Liability and Ownership Issues

The potential liability exposure under environmental laws represents perhaps the single most-significant barrier to private-sector investment in legacy mine-tailings recovery. CERCLA, commonly known as Superfund, establishes strict, joint, and several liability for contaminated sites. Under current legal interpretation, entities that disturb or contribute to the spread of contamination at Superfund sites can become potentially responsible parties liable for cleanup costs even if they did not cause the original contamination and even if their activities ultimately improve environmental conditions [29]. This legal framework creates a powerful disincentive for any entity to engage with legacy tailings sites because the financial liability for site remediation could potentially exceed any revenue from mineral recovery by orders of magnitude.

The fear of inherited liability has long spawned repeated proposals for Good-Samaritan legislation to provide liability protection for entities conducting approved cleanup and recovery activities at abandoned mine lands. Over more than two decades, these proposals would have established pilot programs or permanent frameworks allowing qualified parties to remediate sites without assuming responsibility for pre-existing contamination. In December 2024, Congress finally enacted the Good Samaritan Remediation of Abandoned Hardrock Mines Act (Pub. L. 118–155), which establishes an EPA-administered pilot program authorizing up to 15 Good-Samaritan permits over seven years for remediation of abandoned hardrock mine sites [33]. The EPA is now developing implementation guidance and program procedures, including financial-assurance and permitting guidance released in 2025 [37]. While the Act marks a significant step toward addressing longstanding liability barriers, its limited scope as a pilot program means that important policy and funding gaps remain for many potentially beneficial projects [40].

Ownership and mineral-rights questions create additional legal complexity, particularly for tailings on federal lands or at sites where mineral and surface estates are separately owned. The legal status of minerals in tailings is not entirely clear under the General Mining Law of 1872, which governs hardrock mining on federal lands. Are tailings considered minerals that can be claimed and extracted under mining-law provisions, or are they waste materials that fall under different regulatory frameworks? If tailings on federal land contain recoverable critical minerals, what royalty obligations would apply to their extraction? The lack of clear answers to these questions creates legal uncertainty that increases project risk and complicates financial planning. Recent administrative proposals to clarify the treatment of tailings and establish royalty requirements represent progress toward resolving these ambiguities, but formal rulemaking or liability protection would provide greater certainty [1].

4.6. Economic Viability and Market Risk

The economics of critical-mineral recovery from tailings face inherent challenges stemming from high fixed costs, uncertain revenues, and volatile market conditions. The capital investment required for processing facilities capable of handling the large throughputs necessary to achieve economies of scale can reach hundreds of millions of dollars. These fixed costs must be recovered through product sales over the project life, creating pressure to maintain high utilization rates and avoid operational disruptions. The expanded payback periods typical of capital-intensive mineral-processing operations expose investors to extended market risk because prices and demand conditions a decade hence cannot be predicted with confidence in volatile critical-mineral markets.

Critical-mineral pricing exhibits patterns that create particular challenges for project financing and investment decisions. Unlike major commodity metals, such as copper or zinc, that trade on established exchanges with transparent price discovery and deep liquidity, many critical minerals trade through private negotiations between producers and consumers, with limited price transparency. REE prices, for example, are often negotiated on a case-by-case basis, with significant variation based on purity, quantity, delivery terms, and the relationship between buyer and seller. This opaque pricing makes it difficult to develop robust economic models that financiers can underwrite with confidence. Price volatility compounds the challenge, with some critical minerals experiencing price swings of 50% or more within single years in response to supply disruptions, demand changes, or speculation [41].

The risk of predatory pricing by dominant foreign producers represents a strategic concern that affects investment decisions for domestic critical-mineral projects. China's position in critical-mineral markets provides leverage to influence prices through production adjustments or export policies. A new domestic production facility that requires years to construct and tens or hundreds of millions of dollars of investment could face deliberate price suppression by foreign competitors seeking to strand the investment and maintain market dominance. Historical and recent examples exist of Chinese rare-earth producers reducing prices strategically when new non-Chinese production threatened to enter the market. While trade remedies and government support can potentially mitigate this risk, private investors appropriately consider it when evaluating projects that depend on favorable long-term pricing to achieve returns.

Technical and market uncertainties combine to create financing challenges that extend project-development timelines or prevent projects from proceeding at all. Commercial lenders typically require demonstrated technical viability, secured offtake agreements with creditworthy customers, and conservative economic models showing adequate returns under stressed scenarios. Meeting these requirements for first-of-a-kind tailings-recovery projects can be difficult when comparable precedents do not exist, process performance must be extrapolated from pilot-scale testing, and critical-mineral markets lack the depth and transparency of major commodity markets. The result is that potentially viable projects may struggle to secure financing on acceptable terms, even when technical assessments and base-case economics appear favorable.

4.7. Social License and Community Acceptance

Mining and mineral-processing operations have historically generated conflicts with local communities over environmental impacts, land use, water consumption, and the distribution of economic benefits and costs. These conflicts have created wariness in many mining-affected communities about new industrial activities, even when proposed projects offer environmental improvements and economic opportunities. Developers of tailings-recovery projects must navigate this complex social landscape, building trust with communities that may have experienced broken promises, environmental damage, or economic disruptions from previous mining operations. The challenge is particularly acute at legacy sites where historical mining created ongoing pollution problems as community members may be skeptical that new industrial activity will improve rather than worsen conditions.

Meaningful community engagement requires substantial time and resources, beginning early in project planning and continuing throughout development, construction, and operation. Effective engagement goes beyond minimum legal requirements for public comment to include proactive outreach, transparent information-sharing, genuine consideration of community concerns, and incorporation of community input into project design where feasible. The diversity of community stakeholders which includes local residents, tribal governments, environmental organizations, local businesses, and elected officials means that engagement must employ multiple methods and address varied interests and priorities. The failure to invest adequately in community engagement can result in organized opposition that delays or prevents projects, regardless of their technical merit or environmental benefits.

Tribal consultation represents a particularly important dimension of community engagement for projects on or near tribal lands or affecting resources of cultural or economic significance to tribes. Federal agencies have government-to-government consultation obligations with federally recognized tribes, and many states have similar requirements. These consultations must be conducted respectfully, with appropriate recognition of tribal sovereignty and adequate time for tribal leadership and staff to review project information and provide input. Projects that affect tribal cultural resources, traditional-use areas, or treaty-protected rights face particular scrutiny and require careful attention to tribal concerns. The development of collaborative relationships with affected tribes, including consideration of benefit-sharing arrangements or tribal-employment preferences, can transform potential opposition into support [42].

Community-benefit agreements have emerged as a tool to formalize project commitments to local communities and ensure that benefits are distributed equitably. These agreements, negotiated between project developers and community representatives, can include provisions such as local hiring preferences, training programs to prepare residents for employment opportunities, funding for community infrastructure or services, compensation for potential impacts, or revenue-sharing arrangements that provide ongoing community benefits linked to project success. Well-designed benefit agreements can secure community support by demonstrating tangible local benefits while addressing legitimate concerns about potential impacts. However, the negotiation of such agreements requires good faith on both sides and realistic expectations about what developers can commit to while maintaining project economic viability.

5. CURRENT FEDERAL LANDSCAPE AND INITIATIVES

5.1. Executive Actions and National Strategy

The elevation of critical minerals to a top-tier national priority began during the first Trump Administration in December 2017, with Executive Order 13817, which declared a federal strategy to ensure secure and reliable supplies of critical minerals. This executive order directed the Secretary of the Interior to publish a list of critical minerals and established an interagency working group to develop recommendations to reduce the nation's vulnerability to supply disruptions [43]. The subsequent publication of the first official critical-minerals list by the USGS in 2018 provided a foundation for coordinated federal action by clearly identifying the materials of greatest strategic concern. This initial list, which has been updated periodically to reflect changing market conditions and technological requirements, established the analytical framework that guides federal programs and investments in critical-mineral supply-chain development.

The urgency surrounding critical-mineral security emerged through two major executive actions from the Trump Administration. Executive Order 13817 [44] launched a federal strategy for securing critical-mineral supply chains and identified foreign dependence as a national vulnerability. Executive Order 13953 [45] elevated this concern by declaring a national emergency, determining that reliance on foreign sources poses an unusual and extraordinary threat and authorizing the use of Defense Production Act (DPA) authorities to advance domestic critical-mineral production and processing. This elevation of critical minerals to national-emergency status reflected growing recognition that supply vulnerabilities could constrain America's technological advancement, economic competitiveness, and military capabilities in ways that demanded immediate and sustained federal action.

The Biden Administration maintained and expanded the focus on critical minerals through Executive Order 14017 in February 2021 [46]. The order directed a comprehensive review of supply-chain vulnerabilities across multiple sectors, including semiconductors, large-capacity batteries, pharmaceuticals, and critical minerals. The resulting 100-day supply-chain assessment, delivered in June 2021, identified specific vulnerabilities in critical mineral supply chains and recommended actions to strengthen domestic production, processing, and recycling capacities [45]. Notably, the assessment explicitly included recovery from unconventional sources such as mine waste as a component of the recommended strategy for diversifying supply. This recognition that secondary sources should complement primary mining and international partnerships in a comprehensive supply-security approach provided policy foundation for increased federal investment to develop tailings characterization and recovery technology.

In November 2022, the Biden Administration released fundamental principles for domestic mining reform that explicitly addressed the recovery of critical minerals from mine waste. These principles, developed by an interagency working group led by the Department of the Interior, called for assuring reliable and sustainable critical-mineral supplies through environmentally and socially responsible mining, processing, and recovery from unconventional sources, including mine tailings [46]. The inclusion of tailings recovery within core mining-reform principles signaled recognition at the highest policy levels that this approach deserves strategic support alongside more-traditional mining development. The principles also emphasized the need for strong environmental standards, meaningful tribal consultation, and community engagement; these requirements that apply equally to tailings recovery projects as to conventional mining operations.

The second Trump Administration reaffirmed and elevated the United States' commitment to critical-mineral security on March 20, 2025, by issuing Executive Order 14241 [47]. This Order directs federal agencies to expedite permitting and approvals for domestic mineral projects, prioritizes federal lands for mining and processing development, and delegates authorities under the DPA to support domestic mineral production and processing. By broadening the definition of "minerals" beyond traditional critical minerals to include resources such as copper, zinc, uranium, potash, and gold, Order 14241 signals a strategic shift toward reviving comprehensive domestic supply chains from extraction to refining and manufacturing. The Order thus strengthens the policy foundation for conventional mining, tailings recovery, and secondary-source exploitation, and it conveys a clear message to industry and investors that the federal government now prioritizes minerals security as a core economic and national-security objective.

5.2. Legislative Foundations and Funding

The Energy Act of 2020, enacted as part of broader omnibus legislation, provided the first comprehensive statutory framework for federal critical-minerals programs. This legislation codified the definition of critical minerals, authorized research and development programs focused on extraction and processing technologies and directed federal agencies to support supply-chain development through multiple mechanisms. Significantly, the Act included explicit authorization for research on critical-mineral recovery from secondary and unconventional sources, creating clear legal foundation for DOE programs targeting mine-waste characterization and processing-technology development [1]. The statutory authorization resolved questions about whether discretionary research funding could appropriately be directed toward these applications and established Congressional intent that secondary sources should receive sustained federal support.

The Infrastructure Investment and Jobs Act of 2021 represented a transformative investment in critical-mineral supply-chain development. The legislation appropriated substantial funding across multiple programs relevant to mine-tailings recovery. The Earth Mapping Resources Initiative, managed by the USGS, received enhanced funding to conduct geochemical surveys and mapping of critical-mineral resources, with explicit inclusion of mine-waste sites as targets for characterization [10]. This funding enables systematic assessment of tailings composition across major mining districts, providing the data foundation necessary to inform investment decisions. The appropriation of $3 billion for battery-material processing and manufacturing, while primarily focused on establishing domestic supply chains for lithium-ion battery components, includes provisions that could support recovery of cobalt, nickel, lithium, and other battery-relevant materials from mine tailings.

The invocation of DPA Title III authorities specifically for critical minerals in March 2022 created new mechanisms for federal investment in mining and processing capacity. The presidential determination that authorized DPA use for large-capacity battery minerals explicitly included "by-product and co-product production at existing mining, mine waste reclamation, and other industrial facilities" as eligible activities [48]. This language directly addresses tailings recovery by recognizing that extracting critical minerals from existing mine waste falls within the scope of activities that can receive DPA support. The DoW subsequently made several hundred millions of dollars of DPA funding available for projects that strengthen domestic critical-mineral supply chains, with some awards specifically supporting recovery from secondary sources. The availability of DPA funding provides de-risking capital that can help bridge the gap between pilot-scale demonstration and commercial deployment for tailings-recovery technologies.

The Inflation Reduction Act of 2022 introduced production tax credits and other financial incentives for critical minerals used in clean-energy applications, particularly those incorporated into electric-vehicle batteries and renewable-energy systems. While these incentives primarily target primary production and recycling of end-of-life products, the statutory structure creates indirect benefits for tailings recovery by improving market conditions and price stability for critical minerals, including lithium, cobalt, nickel, and graphite. The requirement that materials benefiting from tax credits meet domestic content or free-trade-agreement sourcing standards creates additional incentive to develop domestic supply sources, including recovery from mine waste, as alternatives to imports from non-aligned nations [49].

The legislative landscape shifted again in 2025 with enactment of the One Big Beautiful Bill Act (Public Law 119-21), which provides the most-sweeping statutory reforms to federal mineral-resource policy in more than a generation. The law strengthens the federal commitment to building secure, domestic critical-mineral supply chains by streamlining permitting processes, expanding access to federal lands for mineral development, and reinforcing agency authorities to support extraction, processing, and refining activities essential to national economic and security priorities. Several provisions complement earlier executive and statutory actions by directing agencies to prioritize mineral-production projects of strategic importance and by authorizing new mechanisms to accelerate infrastructure and industrial-capacity investments. Although implementation will determine the extent to which these reforms benefit unconventional sources such as mine-waste and tailings recovery, the Act establishes a durable legislative foundation that aligns with federal efforts to diversify and expand domestic critical-mineral supplies.

5.3. Regulatory and Permitting Initiatives

Recognition that protracted permitting timelines represent a significant barrier to domestic mining and mineral-processing development has motivated several regulatory reform initiatives. The Federal Permitting Improvement Steering Council, established by the Fixing America’s Surface Transportation (FAST) of 2015, coordinates environmental reviews and authorization processes for major infrastructure projects, including certain mining operations. In 2023, the Permitting Council proposed revisions to its covered project categories that would specifically prioritize critical-mineral mining and processing facilities for coordinated federal review under the FAST-41 framework [50]. This prioritization provides qualifying projects with a single federal coordinating agency, a predictable timetable with specific milestones, and a public dashboard tracking progress through the permitting process. For tailings recovery projects of sufficient scale and significance, FAST-41 designation could substantially compress review timelines and reduce uncertainty relative to traditional permitting pathways.

The Fiscal Responsibility Act of 2023 included provisions reforming the NEPA review process with a stated objective of maintaining rigorous environmental analysis while reducing redundancy and limiting excessive delays. The legislation imposed page limits on EA and EIS documents, established presumptive time limits of 1 year for EAs and 2 years for EISs, and created mechanisms for agencies to incorporate previous EAs by reference, rather than duplicating work [6]. While the practical effect of these reforms on mining-related permitting timelines remains to be demonstrated through implementation, the statutory changes signal Congressional intent to address a barrier that the mining industry and other stakeholders have identified as impeding domestic resource development. Tailings-recovery projects, particularly those at previously permitted sites or integrating with ongoing remediation activities, may benefit from provisions allowing reliance on existing EAs and categorical exclusions for certain activities.

The Council on Environmental Quality has undertaken efforts to clarify how NEPA applies to projects with both environmental-improvement and resource-extraction objectives, a category that encompasses many tailings-recovery scenarios. Guidance addressing how agencies should analyze projects that provide environmental remediation co-benefits alongside mineral recovery could help establish more-consistent and efficient review processes. The development of programmatic EISs covering general categories of tailings-recovery activities in specific regions or deposit types could enable subsequent project-specific analyses to build on comprehensive programmatic reviews, reducing the scope and timeline for individual project approvals. However, progress on these regulatory clarifications has been slower than many stakeholders hoped, and significant uncertainty remains about how agencies will evaluate novel tailings-recovery proposals that do not fit established regulatory templates.

Despite these incremental reforms, federal permitting for mineral-resource projects remains a complex and evolving landscape, particularly for unconventional recovery approaches such as tailings reprocessing. FAST-41 prioritization, NEPA streamlining, and Council on Environmental Quality efforts to clarify environmental-review requirements collectively signal increasing federal recognition that regulatory efficiency is essential to domestic critical-mineral security. However, meaningful acceleration of permitting timelines will depend on consistent implementation across agencies and on clear guidance for projects that blend remediation and resource development. Until those frameworks mature, tailings-recovery initiatives are likely to continue navigating procedural uncertainty, even as policy momentum shifts toward more supportive and predictable regulatory pathways.

5.4. Federal Agency Programs and Roles

The DOE has emerged as the lead federal agency for critical-minerals research, development, and demonstration, with substantial programs managed through the previous Office of Fossil Energy and Carbon Management, the previous Office of Energy Efficiency and Renewable Energy and the Advanced Research Projects Agency-Energy. The recent DOE headquarters realignment has merged most of the critical-materials research and development into one office, entitled the Critical Minerals and Energy Innovation Office. While some DOE critical-minerals programs have focused on coal-based resources, others have addressed mine tailings and hardrock-mining waste explicitly. The Critical Materials Innovation Hub, a DOE Energy Innovation Hub led by Ames Laboratory in partnership with several other national laboratories and universities, conducts research on extraction, separation, and substitution technologies for critical materials across diverse source types. In addition, the METALLIC (minerals to materials supply-chain facility) consortium of nine national laboratories was recently authorized to conduct several research and development projects associated with critical materials that are of high importance. The national laboratories led preliminary data-compilation efforts that assembled the extensive datasets on mine-tailings composition discussed earlier in this report, creating the informational foundation to identify promising recovery opportunities [3].

INL plays a particularly significant role in critical-minerals research and development through its expertise in separation science, chemical engineering, and advanced materials characterization. INL's capabilities in liquid-liquid extraction, ion exchange, membrane separation, and other advanced separation technologies provide a technical foundation to develop efficient and selective recovery processes for critical minerals from complex matrices, including mine tailings. The laboratory's analytical facilities enable detailed characterization of tailings mineralogy and geochemistry at the level of detail necessary to design optimized processing flowsheets. Through cooperative research and development agreements (CRADAs) with private-sector partners, INL has supported pilot-scale demonstrations of critical-mineral recovery technologies, providing de-risking services that help bridge the gap between laboratory proof of concept and commercial deployment [51]. The collaboration of federal-laboratory expertise and private-sector implementation capacity exemplifies the public-private partnership model that will be essential to translate technical capabilities into operational recovery facilities.

The USGS maintains critical responsibilities for resource assessment, data compilation, and geological expertise that support critical-mineral supply-chain development. The Mineral Resources Program conducts fundamental research on mineral-deposit geology, develops assessment methodologies, and compiles data on mineral resources, including mine tailings. The Earth Mapping Resources Initiative (MRI), substantially expanded under the Infrastructure Investment and Jobs Act, conducts geochemical sampling and analysis across mining districts to characterize critical-mineral content in rocks, soils, and mine waste. This systematic characterization effort addresses one of the most-fundamental barriers to tailings recovery by providing the data necessary to identify sites with economically viable critical-mineral concentrations. USGS also maintains the critical-minerals list and provides annual commodity summaries that track global supply-and-demand trends, informing policy decisions and industry planning [52].

The DoW, through its DPA authorities and the Industrial Base Analysis and Sustainment program, has invested in critical-mineral projects that strengthen supply chains for materials essential to weapons systems, electronics, and other defense applications. DoW has particular interest in ensuring availability of materials, including REEs for permanent magnets, cobalt for high-temperature alloys, and platinum group elements for various specialized applications. DoW funding awards have supported projects ranging from rare-earth processing facilities to direct lithium extraction from geothermal brines, demonstrating willingness to invest across the supply chain, from extraction through refining [53]. The potential for DoW procurement commitments to provide stable demand and reduce market risk makes defense applications particularly attractive as initial markets for critical minerals recovered from domestic tailings.

The EPA, while primarily focused on environmental protection and pollution prevention, has roles relevant to tailings recovery through its oversight of mine-waste management, Superfund-site remediation, and water-quality protection. EPA's involvement in tailings-recovery projects can take forms ranging from regulatory oversight that ensures environmental protection to potential financial support for projects that achieve environmental-improvement objectives. Some tailings-recovery scenarios may qualify for Superfund cost recovery or brownfield-redevelopment funding if they demonstrably improve site conditions. EPA participation in interagency working groups on critical minerals helps ensure that environmental considerations are integrated into policy development and that approaches to reconciling resource recovery with environmental protection reflect current scientific understanding and regulatory requirements.

5.5. State-Level Activities

State governments have increasingly recognized critical minerals as strategic priorities and launched their own initiatives to support supply-chain development within their jurisdictions. States with significant mining histories and substantial tailings inventories—including Arizona, Nevada, Montana, Idaho, and Missouri—have particular interest in enabling responsible recovery that can provide economic benefits while addressing legacy environmental issues. Some states have established task forces or working groups specifically focused on critical minerals, bringing together state agencies, academic researchers, industry representatives, and other stakeholders to identify opportunities and barriers. These state-level initiatives can complement and leverage federal programs while addressing jurisdiction-specific circumstances and priorities that may not be adequately captured in national-level policies.

Several states have undertaken efforts to inventory and characterize mine-waste sites within their borders, recognizing that comprehensive data are essential to attract investment and enable project development. State geological surveys have conducted sampling programs, compiled historical mining records, and developed databases documenting tailings locations, volumes, and composition where data exist. These state efforts often collaborate with USGS through the Earth MRI program and other partnerships, creating synergies that extend the reach and impact of limited resources. The integration of state and federal data into accessible databases and mapping tools provides industry with the information necessary to identify and evaluate potential recovery opportunities while helping regulators and communities understand the distribution and characteristics of mine-waste resources.

State permitting processes and regulatory frameworks significantly affect the feasibility and economics of tailings-recovery projects. Some states have developed streamlined permitting procedures for mining operations that provide coordinated multiagency review, firm timelines, and clear standards while others maintain more-fragmented processes that can extend timelines and create uncertainty. States are beginning to examine whether existing permitting frameworks appropriately address tailings reprocessing, which may not fit cleanly into categories designed for conventional mining or waste management. The development of specific regulatory pathways for projects that combine mineral recovery with environmental remediation could reduce approval timelines and regulatory burden while ensuring adequate environmental protection. Montana and Idaho, among others, have explored such tailings-specific regulatory approaches although comprehensive implementation remains limited.

Economic-development agencies in mining-affected states recognize tailings recovery as a potential source of job creation, tax revenue, and economic diversification for communities that have experienced decline following mine closures. Some states have made critical-mineral projects eligible for economic-development incentives, including tax credits, infrastructure investment, workforce-training support, or expedited regulatory review. These state-level incentives can complement federal programs by improving project economics and demonstrating a state's commitment to support responsible resource development. The combination of federal research funding, federal tax incentives, and state economic-development support can create layered benefits that make marginal projects viable or improve returns for projects that would proceed without support, encouraging more-aggressive development of domestic supply capacity.

6. CRITICAL KNOWLEDGE GAPS: THE FOUNDATIONAL BARRIER

6.1. Incomplete Site Characterization Across the Nation

The fundamental obstacle to scaling critical-mineral recovery from mine tailings is not technological capability or processing complexity; rather, it is the absence of reliable comprehensive data characterizing the thousands of tailings sites distributed across the United States. While collaborative efforts between the national laboratories have assembled an impressive compilation of more than 300 datasets from over 100 sources, this achievement simultaneously reveals the magnitude of what remains unknown [3]. The vast majority of mine tailings sites across the nation lack the detailed geochemical characterization necessary to determine whether they contain economically recoverable concentrations of critical minerals, what specific elements are present, how those elements are distributed within the tailings mass, and what mineralogical forms would need to be addressed by processing operations. For purposes of this report, “site characterization” refers to the minimum information needed to evaluate tailings-recovery potential, including approximate tonnage/geometry, bulk geochemistry (including critical elements), mineralogy/speciation, particle size and liberation, spatial variability within the pile, and environmental and handling attributes that constrain processing.

The approximately 300 datasets referenced in this report represent a broad compilation of information on mine tailings drawn from diverse sources, including site-specific studies, regional surveys, historical assay records, and environmental-monitoring data. While some of these datasets do include detailed geochemical measurements for individual tailings sites, the majority do not provide comprehensive, development-grade characterization of specific tailings piles. In many cases, available data document the presence of critical minerals associated with particular deposit types or mining districts, but lack sufficient resolution to define mineralogical form, spatial variability within a tailings pile, or extractability through existing processing methods. As a result, the current data landscape supports high-level identification of where critical minerals are likely to occur in mine tailings, but does not consistently resolve the specific mineral composition or economic potential of individual tailings sites.

The scope of the characterization challenge becomes apparent in considering the historical extent of mining activity in the United States. Hardrock-mining operations have been conducted across the western states and in scattered locations throughout the Midwest, Southeast, and Northeast for more than 150 years. The BLM estimates that hundreds of thousands of abandoned mine features exist on federal lands alone, with additional sites on state and tribal lands and on private property. While not all of these sites involve significant tailings accumulations and many are simply exploration pits or small-scale operations, thousands of locations include substantial deposits, ranging from tens of thousands to millions of tons of material. The precise number of tailings sites exceeding some minimum threshold of potential economic interest remains uncertain precisely because comprehensive inventories do not exist for most states and regions.

Even for sites that are known to exist and have been documented in databases or reports, the available information rarely provides sufficient detail to support investment decisions. A database entry might indicate that a tailings pile exists at a particular location and could estimate its volume based on visual observation or historical-production records, but it may still lack any analytical data on composition. Another entry might include assay results for major elements such as copper, lead, or zinc that were the target of original mining but provide no trace-element analysis that would reveal critical-mineral content. Historical records often describe tailings-disposal practices and locations in general terms, without precise coordinates, making it difficult to locate specific deposits on modern maps or verify their current condition. The heterogeneity of available information reflects the diverse purposes for which data were originally collected (regulatory compliance, environmental assessment, academic research, or industry exploration) rather than systematic characterization for critical-mineral recovery potential.

The technical requirements for characterizing tailings for critical-mineral recovery extend beyond simple elemental analysis to encompass mineralogical characterization, physical-properties assessment, and metallurgical testing. Knowing that a tailings pile contains, for example, 150 parts per million of REEs provides useful preliminary information but does not determine whether recovery is feasible. The specific REE distribution matters because heavy rare earths command much higher prices than light rare earths and may justify recovery at lower total concentrations. The mineralogical form in which rare earths occur determines the processing approach, rare earths in discrete phosphate minerals require different treatment than rare earths substituted into iron oxides or dispersed in clays. Physical characterization of particle-size distribution, density, and magnetic properties informs whether physical beneficiation methods could concentrate target minerals before chemical processing. Metallurgical tests using representative samples establish leaching kinetics, reagent consumption, achievable recoveries, and product purity, providing the data essential for engineering design and economic modeling.

6.2. Fragmented and Inconsistent Data

The data that do exist regarding mine-tailings composition and characteristics suffers from fragmentation across numerous repositories and inconsistency in format, quality, and analytical methods. Federal agencies, including USGS, EPA, the BLM, and the Army Corps of Engineers, maintain separate databases and records related to mine sites and tailings, but these systems were developed independently to serve different programmatic needs and employ different data structures and standards. State geological surveys and environmental agencies maintain their own databases, focused on sites within their jurisdictions. Academic researchers have conducted studies that generated valuable data, but they have published results in dispersed journal articles and reports that may not be indexed in searchable databases. Mining companies possess proprietary information from historical operations that rarely enters the public domain unless required by regulatory processes or voluntarily disclosed.

This fragmentation creates practical barriers to efficiently identifying and evaluating tailings-recovery opportunities. A company or investor interested in potential projects must search multiple databases, contact numerous agencies, review scattered literature, and potentially submit Freedom-of-Information requests to access relevant data. Even after assembling available information, significant effort is required to reconcile different naming conventions for sites, resolve conflicting location coordinates, and compare analytical results obtained using different methods with varying detection limits and accuracy. The time and cost required for data compilation and integration can be sufficiently substantial to discourage preliminary assessment, particularly for smaller companies that lack dedicated research staff or consultants experienced in navigating the complex landscape of mine-waste information.

Inconsistency in analytical methods and reporting standards compounds the challenges created by data fragmentation. Geochemical analyses of tailings conducted over multiple decades have employed varying techniques—including X-ray fluorescence, inductively coupled plasma mass spectrometry, atomic absorption spectroscopy, and other methods—each with different strengths, limitations, and detection limits for specific elements. Critical minerals that occur at trace concentrations may fall below detection limits for some analytical methods or be entirely excluded from analysis suites that focused on major elements and common contaminants. The reporting of results shows similar variation, with some analyses providing full element concentrations while others report only whether concentrations exceed certain thresholds or fall within broad ranges. This analytical heterogeneity makes it difficult to directly compare results from different studies or aggregate data across multiple sites to identify regional patterns or prioritize recovery opportunities.

The temporal dimension adds another layer of complexity to data interpretation. Tailings composition can change over time through weathering processes that dissolve some minerals, precipitate secondary phases, and redistribute elements within the tailings mass. An analysis conducted on fresh tailings immediately after deposition may not accurately represent the composition of the same material after decades of exposure to atmospheric conditions, particularly in humid climates where chemical alteration proceeds rapidly. The lack of time-series data showing how tailings characteristics evolve makes it uncertain whether historical analyses remain representative of current conditions. This uncertainty creates risk for project developers, who must decide whether to rely on existing data or invest in new characterization programs before committing to detailed feasibility studies.

6.3. Lack of Integrated National Database

No comprehensive, standardized, publicly accessible database currently exists that integrates available information on mine-tailings sites across the United States with consistent data fields, quality-control standards, and Geographic Information System capabilities. The absence of such an integrated resource represents a critical gap in the infrastructure necessary to support efficient development of tailings-recovery projects. An effective national database would consolidate information on site locations with precise coordinates, tailings volumes based on surveys or reliable estimation methods, geochemical data showing concentrations of critical minerals and other elements, mineralogical characterization where available, physical-property data, ownership and regulatory status, environmental conditions, and access to infrastructure. This integrated information would enable systematic screening to identify sites with the highest potential for economic recovery based on critical-mineral content, favorable infrastructure, and manageable environmental and regulatory contexts.

The value of an integrated database extends beyond individual site information to encompass regional and national-scale analysis capabilities. Aggregating data across sites would reveal patterns in critical-mineral associations by deposit type, mining district, or geographic region, informing strategic decisions about where to focus characterization efforts and technology-development investments. Statistical analysis of the database could establish baseline concentrations and variability for critical minerals in different tailings types, helping to calibrate economic models and set realistic expectations for recovery potential. Spatial analysis integrating tailings data with infrastructure maps, protected-lands designations, population centers, and other contextual layers would support systematic prioritization of recovery opportunities based on multiple criteria, including resource quality, development feasibility, and strategic importance.

The technical requirements to develop and maintain an effective national tailings database are well within current capabilities, but they require sustained organizational commitment and funding. Modern database architectures can accommodate the diverse data types relevant to tailings characterization, from structured numerical data to spatial coordinates, document images, and analytical metadata. Web-based interfaces can provide public access while implementing appropriate security controls for sensitive or proprietary information. Data-quality standards and validation procedures can ensure that information meets minimum reliability thresholds before inclusion. Importantly, the database structure must accommodate ongoing additions as new characterization work is completed, creating a dynamic resource that grows and improves over time, rather than a static compilation that quickly becomes outdated.

Several models exist for large-scale mineral-resource databases that could inform the design of a national tailings database. The USGS maintains databases on mineral deposits, mining districts, and mineral commodities that integrate diverse data sources with quality-control and public-access features [54]. International examples such as the European Union's ProMine [55] and Minerals4EU [56] projects have demonstrated approaches to aggregating mineral-resource data across multiple jurisdictions with varying data standards and accessibility. The challenge is not technical feasibility; rather, it is organizational coordination and sustained funding to implement and maintain a system of this scope and importance. The return on this investment, measured in terms of enabled private-sector development and improved federal decision-making, would substantially exceed the relatively modest costs of database development and operation.

6.4. Impact on Private-Sector Development and Federal Planning

The incomplete and fragmented state of tailings characterization data directly constrains private-sector investment in recovery projects by increasing uncertainty, extending development timelines, and raising upfront costs to levels that discourage preliminary evaluation. Companies or investors considering potential tailings-recovery opportunities face a fundamental question early in the assessment process: which sites warrant detailed investigation? Without comprehensive data enabling systematic comparison of sites based on critical-mineral content, volume, infrastructure access, and regulatory status, the answer to this question requires expensive, time-consuming site-by-site investigation. A company might invest substantial resources in preliminary assessment of a site based on limited available data, only to discover through detailed sampling that critical-mineral concentrations are lower than preliminary indications suggested or that mineralogical characteristics make recovery economically infeasible with available technologies.

This information asymmetry and associated uncertainty affect project financing at every stage. Early-stage investors and venture-capital funds typically accept higher technical risk in exchange for higher potential returns; nevertheless, investors require sufficient information to estimate probability of success and magnitude of opportunity. The inability to confidently characterize the resource base for tailings recovery, compared to the relatively well-established reserve-estimation methodologies for conventional mining projects, increases perceived risk and may result in higher required returns or complete unwillingness to invest. Later-stage project financing from commercial lenders or strategic investors similarly depends on demonstrated resource confidence based on extensive drilling, sampling, and metallurgical testing. The need to conduct this characterization work from scratch at each site, without the benefit of regional baseline data or comparable site information, extends development timelines and increases costs compared to situations where comprehensive public data would enable more-efficient targeting of detailed investigation.

The data gap affects federal planning and resource allocation in ways that reduce the efficiency and effectiveness of government programs intended to support critical-mineral supply-chain development. Federal agencies that design research funding programs, demonstration projects, or financial incentives for critical-mineral recovery would benefit from understanding the distribution and characteristics of tailings resources to target support where potential impact is greatest. Strategic decisions about which deposit types, geographic regions, or critical-mineral elements should receive priority attention could be better informed by comprehensive data showing where the largest or highest-quality resources exist. The allocation of Earth MRI sampling resources to specific mining districts for characterization would be more efficient if systematic national-scale analysis identified gaps in coverage and prioritized regions based on preliminary indicators of critical-mineral potential.

The absence of comprehensive tailings data also hampers environmental planning and remediation priority-setting. Federal and state agencies responsible for mine-waste cleanup face difficult decisions about where to allocate limited remediation funding for maximum environmental benefit. Some tailings sites with significant pollution problems might also contain valuable critical-mineral concentrations that could make combined remediation and recovery projects feasible, potentially extending remediation budgets by attracting private investment. Without systematic characterization identifying these opportunities, agencies may invest in conventional remediation at sites where recovery opportunities existed, but were not recognized, foregoing potential cost savings and resource conservation. The environmental co-benefits of tailings recovery cannot be systematically pursued without the data infrastructure to identify suitable sites and match them with capable project developers.

Addressing the data gap through a coordinated national characterization program represents the most-impactful single investment the federal government could make to accelerate critical-mineral recovery from domestic mine tailings. The technical work involved, which includes systematic sampling, modern analytical characterization, database development, and results dissemination is straightforward and well within federal-agency capabilities. The USGS possesses the geological expertise, analytical facilities, and data-management experience to lead such an effort. INL and other DOE facilities can contribute advanced analytical capabilities for trace-element characterization and mineralogical analysis. What is required is sustained commitment and adequate funding to execute a comprehensive program over a timeline of perhaps 12–18 months to achieve meaningful national coverage, with ongoing maintenance and expansion as new sites are characterized or priorities evolve. The subsequent sections of this report include specific recommendations on implementing such a program as the foundational element of a comprehensive strategy for critical-mineral recovery from mine tailings.

6.5. Insufficient Research and Development Investments into Economic Separation Technologies

Beyond the challenge of identifying and characterizing tailings resources, a critical gap exists in the development of cost-effective separation and extraction technologies specifically optimized for low-grade, complex tailings matrices. While conventional mineral-processing and hydrometallurgical techniques can technically recover critical minerals from tailings, these methods were designed for primary ores with higher concentrations and simpler mineralogy. The heterogeneous nature of critical minerals in tailings requires fundamentally different technical approaches to achieve economic viability. Current separation technologies frequently prove too energy-intensive, reagent-consumptive, or operationally complex when applied to tailings-recovery scenarios, resulting in processing costs that exceed the value of recovered materials.

While comprehensive national characterization is needed to fully quantify the opportunity, existing data from well-characterized sites demonstrate that current separation technologies are often too energy-intensive or cost-prohibitive when applied to the complex, lower-grade matrices typical of tailings. The research and development investment required to bridge this technology gap has been insufficient relative to the technical challenges already documented at characterized sites, and addressing these challenges is essential to unlock whatever broader opportunities a national assessment program would identify. Federal funding for critical-minerals research has historically focused on primary-resource development rather than secondary recovery from mine waste. While DOE, USGS, and other agencies have supported pilot-scale demonstrations of tailings-recovery technologies, these efforts have been fragmented across multiple programs.

The creation of the Critical Minerals and Energy Innovation Office within DOE provides an opportunity to improve critical-minerals coordination within DOE. National laboratories possess advanced capabilities in separation science, including expertise in solvent extraction, ion exchange, membrane technologies, and emerging approaches such as bioleaching and electrochemical separation. However, systematic application of these capabilities to the specific challenges of tailings processing, particularly for multi-element recovery from complex matrices, requires dedicated long-term research programs that can develop and validate novel flowsheets tailored to different tailings types and deposit-specific mineralogy.

The economic barrier is compounded by the fact that tailings often contain multiple critical minerals in varying concentrations, requiring integrated separation systems capable of selective recovery of individual elements from complex solutions. For example, recovering REEs from phosphate tailings requires not only extracting REEs from the phosphogypsum matrix, but also separating individual lanthanides from each other, a technically challenging and expensive process. Similarly, recovering platinum-group elements from base-metal tailings necessitates separation technologies that can distinguish between chemically similar elements present at part-per-million concentrations in matrices dominated by iron, copper, or other major elements. Without targeted R&D investments to develop selective, energy-efficient, and economically viable separation technologies specifically designed for tailings applications, the vast resource potential represented by domestic mine waste will remain largely inaccessible regardless of how well these resources are characterized. This technology gap represents a foundational barrier that must be addressed through sustained federal investment in applied research, pilot-scale testing, and demonstration programs that advance separation science from laboratory proof-of-concept to commercially deployable systems.

7. RECOMMENDATIONS

The following recommendations provide a comprehensive framework to accelerate responsible development of critical-mineral recovery from domestic mine tailings. These recommendations address the barriers identified in previous sections while building upon existing federal initiatives and leveraging proven approaches from analogous programs. Implementation of these recommendations will require coordinated action across multiple federal agencies, sustained Congressional support through both authorization and appropriation, and active partnership with state governments, tribal nations, industry stakeholders, and affected communities. The recommendations are presented in a sequence that reflects implementation logic, beginning with foundational data development and proceeding through regulatory reform, financial incentives, and institutional-capacity building.

7.1. National Mine-Tailings Assessment Program

Recommendation: Establish a National Mine-Tailings Assessment Program to systematically characterize mine-tailings sites across all major U.S. mining districts within 12 to 18 months, creating a publicly accessible database that enables efficient site identification and project screening.

This recommendation addresses the single most-critical barrier to scaling critical-mineral recovery from mine tailings: the absence of comprehensive, reliable data on site locations, volumes, and critical mineral content. The program should be led by the USGS in partnership with national laboratories, state geological surveys, and other relevant entities. The scope should encompass systematic sampling and analysis of tailings sites in major mining districts across the western United States and other regions with significant historical mining activity, with priority given to districts known to host deposit types associated with critical-mineral enrichment, including copper porphyries, epithermal gold systems, lead-zinc deposits, uranium operations, and phosphate-mining areas.

The technical approach should employ standardized sampling protocols designed to provide representative characterization while managing costs through strategic composite sampling and risk-based analysis tiers. Initial reconnaissance sampling would employ portable X-ray fluorescence or similar rapid techniques to screen sites and identify those warranting detailed characterization. High-priority sites would receive comprehensive analysis using inductively coupled plasma mass spectrometry and other advanced methods capable of detecting critical minerals at economically relevant concentrations. Mineralogical characterization using X-ray diffraction, scanning electron microscopy, and other techniques would determine the forms in which critical minerals occur, informing the selection of a processing approach. All analytical data should be accompanied by rigorous quality-assurance and quality-control procedures, including certified reference materials, duplicate analyses, and interlaboratory comparisons to ensure reliability.

The database component should be designed as a modern, web-accessible and AI-enabled system, with Geographic Information System integration to enable spatial queries and visualization. Core data fields should include precise site coordinates, tailings-volume estimates based on surveys or photogrammetric analysis, comprehensive geochemical data for critical minerals and other elements, mineralogical-characterization results where available, physical property data, ownership and regulatory-status information, environmental baseline conditions, and proximity to infrastructure, including roads, power transmission, and water sources. The database architecture should accommodate diverse data types, including numerical measurements, spatial features, document images, and analytical metadata while implementing appropriate access controls for any sensitive or proprietary information. Public access through an intuitive web interface would enable industry, researchers, and other stakeholders to query the database, download data, and generate custom reports and maps.

Implementation should follow a phased approach that delivers useful results progressively rather than waiting for complete national coverage. Phase one, executable within 6 months, would focus on major porphyry copper districts in Arizona and other southwestern states, epithermal gold districts in Nevada, and lead-zinc districts in Missouri, encompassing perhaps 100–150 priority sites. Phase two would expand to uranium-mining districts, phosphate operations, and additional base and precious-metal mining regions, adding another 200–300 sites over the following 6–12 months. Ongoing maintenance and expansion would continue as new characterization work is completed or priorities evolve. Experience from national programs such as the USGS Earth MRI, which is funded at about $320 million over 5 years, suggests that a realistic budget for comprehensive sampling, analysis, site visits, and database development across 400–500 mine-tailings sites would likely fall in the tens to low hundreds of millions of dollars, yet would remain modest relative to the potential value of the critical-mineral resources identified and the resulting improvements in federal and private-sector decision-making [9].

7.2. Good-Samaritan Liability Protection for Legacy Site Remediation

Recommendation: Enact targeted liability protection under CERCLA and other environmental provisions for qualified entities conducting approved remediation and critical-mineral recovery activities at abandoned mine lands, with pilot-program provisions to demonstrate effectiveness before broader implementation.

The threat of inheriting massive environmental cleanup liability effectively prevents private-sector engagement with many legacy tailings sites that could provide both critical-mineral resources and environmental-improvement opportunities. Good-Samaritan protections should establish clear criteria for qualifying entities, including demonstrated technical and financial capacity to execute proposed work, comprehensive site-characterization and work plans approved by regulatory agencies, enforceable commitments to achieve specific environmental improvements, and financial assurance adequate to complete proposed remediation. The liability protection should shield qualifying entities from responsibility for pre-existing contamination while maintaining accountability for any new contamination resulting from their activities and ensuring that sites are left in improved condition relative to the baseline.

A pilot-program approach would allow testing and refinement of the Good-Samaritan framework before broader deployment. The pilot could authorize perhaps 10–20 projects at carefully selected sites, selected to represent diverse conditions, deposit types, and regulatory contexts. Projects should be required to demonstrate clear environmental improvements through metrics such as reduced metal loading to water bodies, elimination of acid-generation potential, consolidation of dispersed tailings into engineered containment, or removal of physical hazards. Comprehensive monitoring and reporting requirements would document outcomes and identify necessary adjustments to eligibility criteria, approval processes, or oversight mechanisms. Successful pilot demonstrations would build confidence and political support for permanent authorization of a broader Good-Samaritan program.

The solution should specify the relationship between Good-Samaritan liability protection and other legal frameworks, including state environmental laws, property-ownership rights, and tribal sovereignty. Federal preemption of state-liability provisions may be necessary to provide meaningful protection although consultation with states during legislative development could identify opportunities for cooperative frameworks that respect state authority while enabling projects. Clarification of mineral-rights ownership in tailings, particularly on federal lands, should accompany liability protection to ensure that entities have clear legal authority to extract and market recovered materials. Tribal consultation and consent requirements should be specified for projects on or affecting tribal lands or resources, with provisions for benefit-sharing arrangements that ensure tribal communities receive appropriate economic and environmental benefits.

7.3. Streamline Permitting for Remediation-Linked Projects

Recommendation: Develop expedited permitting pathways specifically for critical-mineral recovery projects that achieve measurable environmental improvements, including expanded use of categorical exclusions, programmatic environmental reviews, and FAST-41 prioritization for qualifying projects.

Projects that extract critical minerals from mine tailings while simultaneously remediating environmental contamination should not face the same lengthy, uncertain permitting processes designed for greenfield mining projects that, by definition, disturb previously undisturbed lands. The Council on Environmental Quality should develop guidance clarifying how NEPA applies to remediation-linked recovery projects, establishing presumptions that projects demonstrating net environmental improvements warrant streamlined review. Categorical exclusions should be expanded to cover such activities as sampling and pilot-scale testing at existing tailings sites, reprocessing of limited tailings quantities at permitted facilities, and consolidation of dispersed tailings into engineered containment. These categorical exclusions would enable preliminary project development and technology demonstration without triggering full EIS requirements.

Programmatic EISs covering general categories of tailings-recovery activities in specific regions or for specific deposit types would enable subsequent project-specific reviews to build on comprehensive programmatic analyses. A programmatic EIS might address, for example, REE recovery from phosphate tailings in Idaho and Florida, analyzing general environmental impacts, cumulative effects, and mitigation approaches at a programmatic level. Individual projects conforming to the programmatic framework could then proceed with EAs, rather than full site-specific EISs, substantially reducing documentation requirements and review timelines. The investment in comprehensive programmatic review would be justified by the enabling effect for multiple subsequent projects that tier from the programmatic foundation.

The Federal Permitting Improvement Steering Council should actively recruit significant tailings-recovery projects for FAST-41 designation, providing coordinated federal review with clear timelines and accountability. The Council's recent focus on critical-mineral projects creates favorable conditions for tailings-recovery applications, but proactive outreach and technical assistance would help potential applicants understand eligibility criteria and prepare applications. FAST-41 designation should be accompanied by dedicated staff support from the coordinating agency to manage interagency coordination, resolve disputes, and maintain schedule discipline. Performance metrics tracking approval timelines for FAST-41-designated tailings projects, compared to traditional permitting pathways, would demonstrate program effectiveness and identify opportunities for further improvement.

7.4. Develop Financial Incentives to Attract Private Capital

Recommendation: Implement a suite of financial incentives, including production tax credits, investment tax credits, loan guarantees, and government-offtake agreements that improve project economics and reduce investment risk for critical-mineral recovery from mine tailings.

Production tax credits that provide a specified dollar amount per unit of critical mineral recovered from tailings would directly improve project revenues and help offset the cost disadvantages that tailings recovery may face compared to imports. The credit structure should differentiate by element based on strategic importance and supply risk, with higher credits for materials such as heavy rare earths, cobalt, or platinum-group elements that face severe supply constraints. Credits should be available only for materials meeting domestic-content requirements and sold to domestic purchasers or approved export markets, ensuring that subsidized production strengthens U.S. supply chains, rather than simply substituting for imports. A sunset provision after perhaps 10 years would provide sufficient support for initial market development while avoiding permanent subsidies for mature, competitive industries.

Financing incentives or accelerated-depreciation mechanisms would reduce the capital-cost burden on the construction of tailings-processing facilities. For example, tax incentives similar to those currently available for energy projects would substantially improve project economics and encourage aggressive deployment of processing capacity. The credit should be available for both new-facility construction and major upgrades to existing facilities that add critical-mineral recovery capabilities. Eligibility criteria should require that facilities achieve minimum recovery-efficiency and environmental-performance standards, incentivizing deployment of the best available technologies. Geographic targeting could provide enhanced credits for facilities in economically distressed regions or former mining communities, supporting economic-development objectives alongside supply-chain security goals.

The DOE's Loan Programs Office should establish a dedicated facility for critical-mineral projects with streamlined application processes and terms appropriate for mining and processing operations. Loan guarantees reduce financing costs by shifting default risk from private lenders to the federal government, enabling projects to secure debt at more-favorable interest rates. The program should be capitalized to support perhaps $3–5 billion in loan guarantees, sufficient to enable several major processing facilities while maintaining prudent risk management. Technical assistance from national-laboratory staff during application development would help applicants prepare robust proposals addressing technical, economic, and environmental considerations. Ongoing monitoring throughout project execution would ensure that guaranteed loans are deployed responsibly with appropriate risk mitigation.

Government-offtake agreements providing committed purchase quantities and floor prices would address market risk that discourages private investment in critical-mineral production. The DoW, drawing on DPA authorities and National Defense Stockpile mandates, should negotiate long-term agreements to purchase specified quantities of critical minerals from domestic tailings-recovery operations at prices that ensure project viability. These agreements would provide the revenue certainty that enables project financing while ensuring that the government obtains a reliable supply of materials essential to defense applications. Transparency in pricing and contract terms would prevent windfall profits while maintaining adequate incentives for industry participation. Offtake agreements should be structured to support initial production while including provisions that phase out government purchases as commercial markets develop and mature.

7.5. Update Mining and Mineral Frameworks to Accommodate Secondary Recovery

Recommendation: Comprehensive reform can clarify the legal status of tailings, establish appropriate royalty treatment for minerals recovered from mine waste, and modernize regulatory frameworks to address 21st-century resource recovery while maintaining environmental protection.

The General Mining Law of 1872, which governs hardrock mining on federal lands, does not adequately address reprocessing of mine tailings or recovery from other secondary sources. Legislative reform should explicitly recognize tailings as a mineral resource eligible for location and extraction under appropriate permitting, resolving current ambiguity about legal status. The reform should establish royalty rates for minerals recovered from tailings on federal lands that reflect the reduced resource-extraction costs compared to primary mining while providing fair compensation to taxpayers for public resources. A tiered royalty structure might apply lower rates to tailings recovery than to primary production, acknowledging the co-benefits of environmental remediation and the fact that taxpayers have already accepted environmental impacts from original mining without receiving royalty payments under current law.

Statutory provisions should clarify ownership rights for tailings on federal lands, including whether existing mining claims provide rights to reprocess tailings or whether new claims or permits are required. The framework should balance providing sufficient legal certainty and economic incentive to encourage responsible development against ensuring that public resources are not appropriated without adequate compensation or environmental safeguards. Special provisions may be warranted for tailings recovery projects that achieve significant environmental improvements, potentially including royalty reductions or waivers in cases where environmental benefits exceed thresholds established in regulation. These provisions would create explicit preference for approaches that combine resource recovery with pollution reduction.

The reforms should update environmental and reclamation standards to reflect current best practices while providing appropriate flexibility for tailings-recovery scenarios. Requirements for financial assurance should ensure that adequate funds are available for ultimate site closure and long-term stewardship, with provisions that account for the reduced liability that results from environmental improvements achieved through tailings reprocessing. Reforms should require ongoing monitoring and adaptive management, requiring operators to demonstrate continuous environmental improvement and adjust practices in response to monitoring results. Public participation and transparency provisions should ensure that communities and stakeholders have meaningful opportunities to engage in decision-making processes affecting projects in their regions.

7.6. Strengthen National Laboratory Partnerships and Technology Transfer

Recommendation: Expand the role of relevant national laboratories in supporting critical-mineral recovery through streamlined CRADA, expanded DOE-funded voucher programs, and other agreements, establishment of user facilities for pilot-scale testing to derisk systems for industry, and formalized technology-transfer mechanisms that accelerate commercial deployment.

Relevant national laboratories possess specialized expertise in separation science, chemical engineering, and advanced materials characterization that positions them as valuable partners for industry efforts to develop and optimize tailings processing technologies. A coordinated approach across DOE national laboratories could establish dedicated Critical Minerals Recovery Research and Development Centers that provide state-of-the-art analytical facilities, pilot-scale processing equipment, and expert technical support to private sector partners developing recovery technologies. These centers would operate under a user-facility model similar to successful programs in other technical domains, with industry partners gaining access to capabilities they could not economically maintain in-house while national laboratory staff gain practical experience with real-world applications that inform their fundamental research programs.

DOE-funded voucher programs should be significantly expanded to enable direct collaboration between national laboratories and industry partners for critical-minerals recovery-technology development and deployment. These voucher programs would provide industry with no-cost or cost-shared access to national-laboratory expertise, facilities, and pilot-scale testing capabilities, dramatically accelerating the transition of promising technologies from laboratory development to commercial deployment. Voucher programs have proven effective in other energy-technology sectors and could be tailored specifically for critical-minerals recovery, with priority given to projects addressing tailings reprocessing, advanced separation technologies, and environmental remediation co-benefits. By reducing financial barriers to industry-laboratory partnerships, voucher programs would enable smaller mining companies and technology startups to access world-class capabilities that would otherwise be beyond their reach, fostering innovation across the full spectrum of potential tailings-recovery opportunities.

CRADAs should be expanded in scope and number to enable more-extensive collaboration on tailings-specific processing challenges. For example, national laboratories have demonstrated success in CRADA partnerships that combine laboratory expertise in areas such as solvent extraction and hydrometallurgical separation with industry knowledge of specific feedstocks and market requirements. Among others, INL has contributed expertise in separation science and advanced materials characterization through such partnerships. Expanding this model to encompass a broader portfolio of deposit types and target-element combinations would accelerate technology development across the full range of tailings-recovery opportunities. Federal funding support for laboratory participation in CRADAs, potentially through DOE appropriations specifically designated for critical-mineral partnerships, would enable more aggressive engagement without requiring industry partners to bear the full cost of laboratory time and facilities.

Formalized technology-transfer mechanisms should ensure that successful approaches developed through government-funded research reach commercial deployment efficiently. The national-laboratory system has established pathways for technology licensing, but these could be streamlined specifically for critical-mineral technologies given their strategic importance. Priority licensing processes, reduced or waived licensing fees for domestic manufacturers, and active matchmaking between technology developers and potential industrial adopters would accelerate the translation of laboratory innovations into operating facilities. The DOE should establish metrics and incentives that reward laboratories for successful technology transfer measured by industrial implementation and production of critical minerals from domestic sources, aligning institutional priorities with national strategic objectives.

7.7. Workforce Development and Education Programs

Recommendation: Establish a comprehensive national workforce-development initiative to rebuild mining, minerals processing, and earth-science academic programs while attracting and training the skilled workforce necessary to support critical-mineral recovery from mine tailings and broader domestic supply-chain development.

The decades-long decline in U.S. university programs focused on mining engineering, extractive metallurgy, economic geology, and related earth sciences has created a critical shortage of domestic expertise precisely when national strategic priorities demand expanded domestic critical-mineral production and processing capacity. Many universities have eliminated or severely reduced these programs, with faculty positions going unfilled, laboratory facilities being repurposed, and student enrollment declining to unsustainable levels. This erosion threatens to constrain domestic critical-mineral development regardless of resource availability or technological capability because the trained workforce necessary to design, construct, operate, and optimize recovery facilities will not exist in sufficient numbers.

A coordinated approach to workforce development could address needs across multiple career stages and educational pathways. Competitive grant programs could support the establishment or revitalization of academic programs in mining engineering, mineral processing, economic geology, and separation science at institutions near major mining regions or national-laboratory facilities. Such programs could fund endowed faculty positions for long-term stability, modern laboratory and pilot-scale equipment for hands-on training, graduate fellowships and undergraduate scholarships to attract talented students, and curriculum development integrating emerging technologies with traditional fundamentals. Programs establishing formal partnerships with industry and national laboratories would ensure academic training aligns with industry needs through internships, cooperative education, and collaborative research, providing students with practical experience that complements classroom instruction.

Beyond traditional 4-year degree programs, community colleges and vocational institutions represent important pathways for preparing technicians, operators, and skilled tradespeople for tailings-recovery operations and critical-mineral processing facilities. Many former mining communities possess community colleges that could develop certificate and associate-degree programs in mineral processing, analytical chemistry, environmental monitoring, and equipment operation if provided with appropriate equipment, curriculum support, and industry partnerships. Standardized curricula deployable across multiple institutions would ensure consistent quality while avoiding duplication of effort. Mobile training laboratories or partnerships with existing processing facilities could provide hands-on training in regions where permanent facilities have not yet been established.

Expanded scholarship and fellowship programs targeted at critical-minerals disciplines could attract talent by providing competitive financial support comparable to other science, technology, engineering, and math fields, reducing the economic disincentive that currently discourages students from pursuing careers in mining and mineral processing. Loan forgiveness provisions for graduates who commit to working in domestic critical-mineral operations for specified periods could further incentivize career choices supporting national objectives. Graduate fellowships prioritizing research on tailings recovery, advanced separation technologies, and environmental remediation would create a pipeline of Ph.D.-level expertise capable of driving continued innovation.

National laboratories could expand their workforce-development role through enhanced postdoctoral programs, visiting-faculty appointments, and summer research opportunities for graduate and undergraduate students. These programs leverage world-class facilities and expertise while exposing early-career researchers to cutting-edge separation science, analytical capabilities, and real-world processing challenges. Laboratory staff serving as adjunct faculty at nearby universities can strengthen academic programs while maintaining laboratory connections to the next generation of professionals. Industry partnerships—including commitments to hire graduates, provide internships, and contribute expertise through guest lectures and curriculum review—would create clear pathways from education to employment. The development of industry-recognized professional certifications in critical-mineral processing and mine-waste remediation could establish quality standards and career-progression frameworks benefiting both employers and workers.

Retraining programs could support workers transitioning from declining industries into growing critical-minerals sectors, leveraging existing skills in chemical processing, heavy industry, or skilled trades while providing specific knowledge of mineral processing, analytical methods, and environmental compliance. Community colleges in former mining regions are well positioned to offer accelerated programs preparing experienced industrial workers for positions in tailings-recovery operations. Veterans' education benefits could be explicitly applicable to critical-minerals training programs, recognizing the alignment between military experience and the safety-critical nature of mineral-processing operations.

Workforce-development investments would benefit from clear metrics assessing enrollment trends, graduation rates, employment outcomes, and employer satisfaction with graduate preparation. Industry input through formal advisory mechanisms could guide program priorities and curriculum updates, maintaining relevance as technologies and business needs evolve. Without adequate numbers of trained professionals, investments in resource characterization, technology development, and financial incentives cannot translate into operational recovery facilities producing materials essential to national defense, economic competitiveness, and technological leadership. Workforce development represents a foundational enabler that determines whether other strategic initiatives can achieve their intended impact.

7.8. Ensure Robust Environmental and Community Safeguards

Recommendation: Establish mandatory environmental and community-engagement standards for critical-mineral recovery projects that ensure net environmental improvement, meaningful public participation, respect for tribal sovereignty, and equitable distribution of benefits and burdens.

All tailings-recovery projects, regardless of scale or funding source, should be required to demonstrate net environmental improvement compared to baseline conditions. This requirement should be enforced through clear performance metrics, including reductions in metal loading to water bodies, elimination or substantial reduction in the potential for acid generation, consolidation of dispersed tailings into engineered containment that meets current standards, reduction in fugitive dust emissions, and improvement in site stability and public safety. Projects should be required to establish baseline conditions through comprehensive environmental characterization before commencing operations and conduct ongoing monitoring to verify that improvements are achieved and maintained. Independent third-party verification of environmental performance should be required at key project milestones to ensure objectivity and build public confidence.

Financial-assurance requirements should ensure adequate funding for site closure and long-term stewardship, regardless of a project's economic performance. Bonding levels should be calculated based on worst-case closure scenarios and adjusted periodically to account for inflation and changing site conditions. The assurance mechanisms should be structured to survive corporate bankruptcy or project abandonment, potentially through trust funds, letters of credit, or other instruments that remain accessible even when the operating entity ceases to exist. Provisions should require operators to conduct progressive reclamation, remediating areas no longer needed for active operations rather than deferring all reclamation to final closure. This approach reduces ultimate closure costs and demonstrates ongoing commitment to environmental responsibility.

Community engagement should begin early in project planning and continue throughout the project life cycle, with meaningful opportunities for public input to influence project design and operations. Developers should be required to establish community advisory committees that include representatives from local government, residents, environmental organizations, and other stakeholders meeting regularly and transparently sharing information. Community-benefit agreements should be encouraged as mechanisms to ensure local communities share in the project's economic benefits through employment preferences, revenue sharing, infrastructure investments, or other negotiated provisions.

Tribal-consultation requirements should reflect the government-to-government relationship between federal agencies and federally recognized tribes, with early engagement, adequate time for tribal review and input, and genuine consideration of tribal concerns in decision-making. Projects on tribal lands should require tribal consent through appropriate tribal governance processes. Projects affecting a tribe's cultural resources, traditional use areas, or treaty-protected rights should involve collaborative development of mitigation measures and monitoring protocols. Benefit-sharing provisions for projects on or near tribal lands should be negotiated through government-to-government consultation, with frameworks that respect tribal sovereignty while ensuring tribes receive appropriate economic benefits and environmental protections.

7.9. Expand Research, Development, and Demonstration Programs

Recommendation: Establish regional Critical Minerals Recovery Research and Development Centers at strategic national laboratories, funded through dedicated base appropriations rather than competitive mechanisms, to provide sustained infrastructure, expertise, and collaboration platforms for industry and academic partners developing tailings-recovery technologies. Regional centers based at national laboratories should be established to address specific technical challenges identified in tailings-recovery applications, with each center receiving dedicated base funding for staff, equipment, and facilities. These centers would focus on priority technical areas, including:

- The development of selective and economical leaching approaches that minimize dissolution of gangue minerals while maximizing extraction of target elements
- Advanced separation technologies capable of efficiently separating chemically similar elements, such as individual rare earths or platinum-group elements
- Novel biological approaches including bioleaching and biosorption that could reduce energy consumption and hazardous reagent use
- Integrated processing systems that co-recover multiple critical minerals from complex tailings matrices.

Each regional center would be funded through dedicated DOE base appropriations that provide stable, long-term support for permanent staff positions, state-of-the-art analytical and processing equipment, and pilot-scale facilities. Rather than competing for project-by-project funding, centers would receive sustained base funding to maintain core capabilities and infrastructure. Competitive funding mechanisms would instead be directed toward industry partners and academic institutions to collaborate with the centers, enabling companies and universities to access center capabilities through grants, vouchers, or cost-shared partnerships. This model ensures that critical infrastructure and expertise remain available regardless of funding cycles while competition focuses on identifying the most-promising industry applications and academic innovations that can leverage center resources.

Regional centers would operate pilot-scale demonstration facilities capable of processing 10–100 tons per day of tailings through complete flowsheets, providing the engineering data, operational experience, and economic validation necessary for commercial-scale deployment. Base funding would support center infrastructure and core capabilities while competitive grants to industry partners would enable them to demonstrate their specific technologies and processes using center facilities. Priority demonstration projects would address high-impact opportunities, including rare-earth recovery from phosphate or uranium tailings, cobalt and nickel recovery from base-metal tailings, and platinum-group element recovery from historic mining operations. Industry partners would contribute cost-sharing and intellectual property while benefiting from access to capabilities that would be prohibitively expensive to develop independently.

Each center would maintain comprehensive databases documenting operating parameters, recovery efficiencies, reagent-consumption rates, energy requirements, and economic performance from all projects conducted using center facilities. Non-proprietary results would be publicly disseminated to accelerate learning across the industry and prevent duplication of effort. Industry partners accessing center facilities through competitive grants or vouchers would retain intellectual-property rights to their proprietary innovations while contributing to the shared knowledge base for non-proprietary operational data. This balanced approach ensures that taxpayer-funded infrastructure generates broadly accessible knowledge while still providing sufficient incentives for private-sector innovation. Geographic distribution of centers across major mining regions would ensure proximity to diverse tailings resources and facilitate collaboration with regional industry clusters, with each center developing specialized expertise relevant to local deposit types and processing challenges.

7.10. Government Procurement and Market Support

Recommendation: Leverage federal procurement authorities and the National Defense Stockpile to create stable demand and reduce market risk for critical minerals recovered from domestic mine tailings while developing market infrastructure to facilitate transactions between producers and end-users.

The DoW should actively use its procurement authorities to purchase critical minerals from domestic tailings-recovery operations for direct use in defense applications and for strategic stockpile replenishment. Long-term purchase agreements with price floors would provide the revenue certainty necessary to justify private investment in processing facilities while ensuring that the military obtains reliable domestic supply of materials essential to weapons systems, electronics, and other applications. The agreements should be structured to support initial production from first-of-a-kind facilities during the critical early years when market risks are highest, with provisions to phase out government purchases as commercial markets mature and can absorb production without price support. Transparent pricing linked to verifiable market indices would prevent windfall profits while maintaining adequate returns to justify continued investment and expansion.

The National Defense Stockpile should be actively managed to support critical-mineral market development, rather than simply warehousing materials purchased in previous decades. Strategic releases of stockpiled materials could stabilize prices during supply disruptions, preventing the extreme price volatility that discourages industrial investment in applications requiring critical minerals. Conversely, strategic purchases during periods of oversupply could provide price support that prevents economically viable domestic production from being idled by temporary market downturns or predatory pricing by foreign competitors. This active-management approach would require enhanced analytical capabilities to monitor global supply and demand, model price dynamics, and execute well-timed interventions, but the benefits in terms of supply security and industrial stability would justify the investment in this expertise.

Federal agencies should support development of market infrastructure that facilitates efficient transactions between diverse producers and consumers of critical minerals. Many critical minerals lack the transparent spot markets, futures contracts, and well-established trading relationships that characterize major commodity metals. This opacity creates friction in matching supply with demand and increases transaction costs. Government could support industry efforts to develop market-making functions, information exchanges that publish indicative prices and available quantities, and standardized specifications that enable fungible products to be traded more efficiently. The National Institute of Standards and Technology could develop certified reference materials and analytical standards for critical minerals in various forms, enabling producers to demonstrate product quality and buyers to verify specifications. These market-infrastructure investments would benefit all participants by reducing transaction costs and improving liquidity, supporting industry growth without ongoing subsidies.

7.11. Establish a Federal Critical-Minerals Processing Hub on DOE-Managed Land

Recommendation: Designate and develop a centralized critical-minerals processing hub on DOE-managed federal land to serve as a national-scale facility for the receipt, processing, separation, and refining of critical minerals recovered from domestic mine tailings and other secondary sources, integrating the full mineral-processing value chain under a unified regulatory and operational framework.

One of the most-persistent structural barriers to tailings-based critical-mineral recovery is the absence of viable downstream processing. Individual tailings sites are geographically dispersed and typically lack the scale, infrastructure, and capital necessary to justify dedicated separation and refining circuits through the full value chain. A centralized hub resolves this mismatch by decoupling extraction from processing: raw or partially concentrated feedstocks from distributed sites. Feedstocks are transported to a central facility where they undergo hydrometallurgical leaching, multi-stage solvent extraction or ion-exchange separation, and final refining to produce high-purity oxides, sulfates, and metals meeting domestic manufacturing and defense specifications. This approach mirrors successful centralization models in petroleum refining and semiconductor manufacturing. A hub focusing on metals prioritized by DOE's Critical Minerals and Energy Innovation Office would spread fixed processing costs across feedstocks from dozens or hundreds of contributing sites, making viable those projects that could not justify standalone processing infrastructure.

Siting the hub on a DOE reservation offers compelling regulatory and institutional advantages. Existing DOE reservations possess established security perimeters, environmental-monitoring programs, electrical-transmission capacity, and transportation corridors developed over decades of industrial operation. Consolidated federal oversight substantially reduces permitting fragmentation: individual contributing tailings sites would require only extraction-stage permits, while a single comprehensive permitting and NEPA review covers the full range of hub processing activities. Hub operations would also be well positioned to leverage DPA authorities, production tax credits, and loan guarantees under a unified administrative framework, concentrating federal financial support for maximum leveraged impact. A resident national laboratory presence at or affiliated with the hub would provide continuous access to advanced characterization equipment and separation-science expertise, enabling tight feedback between research and operational practice consistent with the partnership model described in Recommendation 7.6.

A structured industrial tolling program would allow private-sector companies to purchase processing access scaled to their individual operations, converting the $100–300 million capital requirement for full downstream processing into a predictable variable operating cost and reducing required upfront investment to the $15–50 million range needed for extraction and feedstock preparation alone. Capacity allocations would be awarded based on strategic value of the target mineral suite, the supply-chain vulnerabilities addressed, and environmental remediation co-benefits achieved, with a published sliding-scale fee structure calibrated to feedstock grade and processing complexity. Implementation should proceed in three phases: site selection and programmatic environmental review within 12 months of authorization; construction and commissioning of a pilot-scale module processing 500–1,000 tons per day within 18–36 months; and expansion to commercial-scale throughput of 5,000–20,000 tons per day thereafter, based on demonstrated pilot performance and feedstock volumes identified through the National Mine Tailings Assessment Program described in Recommendation 7.1. The hub thus serves as the integrating operational centerpiece of the broader strategy described in this report, transforming the dispersed potential of domestic tailings resources into a reliable domestic supply of refined critical minerals.

8. CONCLUSION

The United States stands at a critical juncture in its approach to critical-mineral supply security. Decades of policy choices, economic pressures, and global competition have created a situation in which the nation depends heavily on geopolitical adversaries and potentially unreliable partners for materials essential to national defense, economic competitiveness, and technological leadership. This dependence represents more than an economic inconvenience or a matter of industrial policy optimization; it constitutes a fundamental strategic vulnerability that constrains U.S. freedom of action in an increasingly contested international environment. The accelerating deployment of advanced-energy technologies, the electrification of transportation, the ongoing digital transformation of the economy, and the sophistication of modern weapons systems all increase demand for critical minerals at rates that far exceed historical consumption patterns. Meeting this growing demand from secure, reliable sources requires urgent action across multiple dimensions, including primary mining development, international partnerships, enhanced recycling, and recovery from unconventional sources.

Among these approaches, the recovery of critical minerals from domestic mine tailings offers unique advantages that justify prioritization within a comprehensive supply-security strategy. The resource base is substantial, with billions of tons of tailings distributed across thousands of sites containing recoverable quantities of REEs, cobalt, gallium, germanium, platinum-group elements, and other strategic materials. The technical capabilities to extract and separate exist today, built on decades of metallurgical innovation and separation-science advancement. Many tailing sites represent ongoing environmental liabilities, the remediation of which through mineral recovery would achieve the rare convergence of economic and environmental objectives, simultaneously strengthening supply chains and cleaning and containing legacy pollution. The infrastructure, workforce, and regulatory frameworks associated with historical mining districts provide foundations upon which recovery operations can build more quickly and cost-effectively than entirely new mining developments in remote, undeveloped locations.

Yet despite these compelling advantages, the development of critical-mineral recovery from mine tailings has proceeded slowly, with only a handful of operational projects and limited private-sector investment compared to the scale of opportunity. The barriers are not primarily technical although process optimization and cost reduction remain ongoing challenges. Rather, the obstacles are fundamentally related to incomplete information, regulatory uncertainty, economic risk, and institutional frameworks designed for conventional mining rather than the hybrid resource-recovery and environmental-remediation model that tailings reprocessing represents. The single most-critical barrier is the absence of comprehensive, reliable data characterizing the thousands of tailings sites across the nation. Without this foundational information, private-sector developers cannot efficiently identify promising opportunities, investors cannot confidently evaluate project economics, and federal agencies cannot strategically allocate support to maximize impact.

The recommendations presented in this report provide a roadmap for overcoming these barriers through coordinated federal action. The National Mine Tailings Assessment Program would address the data gap that currently constrains all other aspects of development, creating within 12 to 18 months the comprehensive site characterization necessary to unlock private investment and enable informed planning decisions. Good-Samaritan liability protection would remove the legal disincentive that prevents engagement with legacy sites where the potential for environmental improvement through recovery operations is greatest. Streamlined permitting pathways would compress approval timelines for projects that achieve measurable environmental benefits while maintaining rigorous analysis of potential impacts. Financial incentives in the form of production tax credits, investment credits, loan guarantees, and/or government offtake agreements would improve project economics and reduce the investment risk that makes critical-mineral recovery less attractive than conventional mining or imports, despite its strategic value.

Mining reform would update legal frameworks designed in the 19th century to address 21st-century resource-recovery realities, clarifying ownership, establishing appropriate royalty treatment, and ensuring that public resources generate fair returns for taxpayers while incentivizing responsible development. Enhanced national-laboratory partnerships would leverage the world-class expertise of relevant national laboratories and other federal facilities to accelerate technology development and de-risk commercial deployment through pilot-scale demonstrations and technical support. Robust environmental and community safeguards would ensure that the pursuit of supply security does not repeat past mistakes, instead demonstrating that modern resource development can achieve high environmental standards and equitable benefit distribution. Expanded research, development, and demonstration programs would advance the frontiers of separation science and metallurgical processing while proving integrated systems at scales relevant to commercial decision-making. Strategic use of government procurement would create stable markets and price support during the critical early years when market risks are highest and private investors most hesitant. A federal critical-minerals processing hub on DOE-managed land would serve as the integrating operational centerpiece, transforming feedstocks from distributed tailings sites into specification-grade refined materials through shared infrastructure and streamlined federal oversight.

These recommendations are mutually reinforcing rather than independent alternatives. The data from a national assessment program inform strategic deployment of financial incentives by identifying where support would have greatest impact. Good-Samaritan protections enable projects at legacy sites that the assessment identifies as high-priority opportunities. Streamlined permitting accelerates deployment of technologies developed through national-laboratory partnerships and demonstrated with federal research funding. Government procurement provides markets for materials recovered at facilities financed through federal loan guarantees or tax incentives. The integrated implementation of this framework would create conditions under which responsible tailings recovery can scale from today's handful of pilot projects to a meaningful component of domestic critical-mineral supply within the current decade.

The urgency of implementation cannot be overstated. Global competition for critical-mineral supply chains is intensifying as nations recognize that control over these materials confers significant economic and strategic advantages. China continues to consolidate its dominance across mining, processing, and manufacturing of products enabled by critical minerals while other nations, including European Union members, Japan, South Korea, and Australia, aggressively pursue policies to secure their own supply chains. The United States cannot afford extended deliberation or incremental half-measures while competitors move decisively to lock in advantaged positions. The imperatives of energy independence, manufacturing competitiveness, and national security, driven by both strategic necessity and economic opportunity, demand immediate action to secure domestic critical-mineral supply chains. The defense industrial base requires reliable access to critical minerals now, not in some indefinite future after protracted permitting battles and market-development struggles.

The window for effective action may be limited. Current bipartisan recognition of critical-mineral supply security as a national priority creates favorable political conditions for the investments and reforms recommended in this report. The combination of national-security concerns, economic-competitiveness objectives, and environmental co-benefits provides a coalition of support spanning traditional ideological and partisan divides. However, political windows can close as priorities shift or as the difficulty of implementation generates opposition from affected interests. The federal government should move expeditiously to establish programs, create legal incentives and protections, and commit resources while consensus for action remains strong.

The path forward requires partnership across government, industry, academic institutions, and communities. Federal agencies bring resources, expertise, and policy authorities essential for addressing market failures and coordinating action at national scale. Private-sector companies provide the investment capital, operational capabilities, and market discipline necessary to build and operate efficient, cost-effective processing facilities. National laboratories and universities contribute cutting-edge research capabilities and train the workforce that will design and operate future recovery operations. State and local governments provide on-the-ground knowledge, regulatory implementation, and connections to affected communities. Tribal nations bring sovereign authority over significant land areas and resources, along with traditional knowledge and perspectives that can inform responsible development. Communities hosting tailings sites and recovery operations must be genuine partners in decisions affecting their environments and economies, with meaningful opportunities to influence outcomes and share in benefits.

The transformation of mine tailings from environmental liabilities into strategic assets represents more than a technical challenge or a policy problem to be solved. It exemplifies a broader imperative to rethink how the United States manages resources, addresses legacy environmental issues, and positions itself for success in an era of intensifying global competition. The creative reuse of materials previously discarded as waste, the integration of environmental improvement with resource recovery, and the development of domestic supply capacity for strategically essential materials all reflect adaptive responses to changing circumstances and evolving priorities. Success in this endeavor would demonstrate that the United States retains the institutional capacity, technical capability, and political will to address complex challenges requiring coordination across multiple sectors and sustained commitment over years.

The opportunity before the nation is clear. Billions of tons of mine tailings containing significant quantities of critical minerals exist in known locations across the United States. The technologies to extract these materials are available or achievable through focused development efforts. The environmental benefits of remediation through recovery are substantial and measurable. The economic potential for job creation and industrial development in mining-affected regions is significant. The strategic value of reduced import dependence and enhanced supply security is undeniable. What remains is marshaling the political will, committing the necessary resources, implementing the policy reforms, and sustaining the effort required to realize this potential. The recommendations in this report provide the framework. The time for implementation is now. The stakes, which include national security, economic prosperity, environmental quality, and technological leadership, could not be higher. The choice is whether to seize this opportunity to transform yesterday’s mining waste into tomorrow’s strategic resource or to accept continued dependence on foreign sources for materials essential to the nation’s future.

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