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Environmental Impacts of Rare Earth Element Production: A Review of Soil Acidification, Radioactive Tailings and Heavy-Metal Pathways

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Abstract: **Rare earth elements (REEs) are a group of chemically similar lanthanides, commonly discussed together with yttrium and scandium, that underpin permanent magnets, catalysts, polishing powders, phosphors, batteries and many low-carbon technologies. Their environmental profile is therefore paradoxical: the same materials that help reduce emissions in wind turbines, electric vehicles and high-efficiency electronics can create serious local burdens when ores are mined and processed without strong containment. This review evaluates three dominant impact pathways in REE production: soil acidification, radioactive tailings and heavy-metal or metalloid contamination. The review uses a standard source-pathway-receptor framework because the severity of each issue depends not only on total contaminant concentration, but also on geochemical mobility, hydrology, exposure duration, land use and the effectiveness of operational controls.**

The strongest evidence for soil acidification comes from ion-adsorption clay mining, where ammonium-salt leaching leaves residual ammonium in highly weathered soils. Subsequent nitrification releases hydrogen ions, lowering pH and increasing the mobility of aluminum, manganese, REEs and co-occurring heavy metals. Recent field evidence from southeast China shows that mined ion-adsorption tailing soils had lower pH than unmined soils and that pH declined with mining age, linking residual ammonium and nitrate formation to long-term acidification (Xu et al., 2023). Radioactive tailings are most important for deposits containing monazite, xenotime and some carbonatite-related minerals because thorium, uranium and radium can be redistributed and concentrated in tailings, slimes and residues. Field gamma surveys around Baotou and Bayan Obo show that radiological issues require site-specific measurement rather than assumption (Li et al., 2016). Heavy-metal risks arise from ore gangue, processing reagents, acidification-driven desorption and dust or sediment transport, with studies from ion-adsorption mining areas showing contamination of water, sediment and agricultural soils (Liu et al., 2019). Overall, the literature indicates that REE impacts are controllable, but only if mining plans integrate nitrogen management, tailings engineering, radiological monitoring, water treatment, dust control, progressive reclamation and long-term post-closure surveillance.

Keywords: **Rare earth elements (REEs), Soil Acidification, Radioactive Tailings, Heavy-Metal Pathways.**

1. INTRODUCTION

Rare earth elements occupy an unusual position in modern environmental debates. They are essential to technologies that are often framed as environmentally beneficial, including neodymium-iron-boron magnets for wind turbines and electric vehicle motors, lanthanum and cerium in catalytic and polishing applications, europium and terbium in phosphors, and a broader suite of REEs in electronics, defense systems and energy infrastructure. However, the mining and processing chain for REEs can impose localized burdens on soils, sediments, water, workers and nearby communities. The environmental contradiction is not that REEs are uniquely toxic in all circumstances. It is that many REE ores are

chemically complex, low grade, fine grained or associated with thorium, uranium, fluorides, sulfides, ammonium salts and heavy metals. Production therefore requires large material throughput and aggressive chemical processing, which can convert a geologically stable ore body into mobile contaminants.

A defensible review of REE environmental impacts must distinguish between three related but different questions. The first is the intrinsic chemistry of REEs and associated elements. REEs tend to form trivalent cations, complex with carbonate, sulfate, phosphate and organic ligands, and sorb strongly to iron and manganese oxides and clay minerals under many environmental conditions. The second question is the industrial pathway by which ore is extracted, beneficiated, leached, separated and refined. Different deposit types have different risk profiles: ion-adsorption clays create nitrogen and acidification concerns; monazite-bearing sands and hard-rock ores create radiological residue concerns; sulfide-bearing or metal-rich gangue can generate acid drainage and heavy-metal mobility. The third question is exposure. A high concentration inside a lined, monitored tailings facility is not the same risk as a lower concentration dispersed into agricultural soil, surface-water sediment or household dust. The source-pathway-receptor model is therefore the organizing logic used throughout this review.

The review focuses on soil acidification, radioactive tailings and heavy metals because these are the pathways most frequently highlighted in field studies, regulatory reviews and life-cycle assessments. Soil acidification matters because pH is a master variable controlling nutrient availability, microbial activity, root function and contaminant mobility. Radioactive tailings matter because thorium and uranium decay chains can generate external gamma exposure, radon, long-lived residues and waste-management obligations. Heavy metals matter because elements such as lead, cadmium, arsenic, chromium, nickel, manganese and zinc may be co-released with REEs or mobilized under acidic conditions, affecting water quality, crop safety and ecological receptors. The three pathways interact: acidification increases metal mobility; tailings dust can deliver metals and radionuclides to soils; and drainage from residues can connect waste storage to downstream sediment.

The aim is not to portray REE production as environmentally unacceptable in every setting. Rather, the objective is to provide a thesis-defence-ready synthesis of what is known, where the strongest evidence comes from, how the pathways operate, and which controls are most credible. High-impact sources are prioritized, including Science of the Total Environment, Chemosphere, Journal of Environmental Radioactivity, Environmental Science & Technology, Journal of Hazardous Materials, Nature Sustainability, Resources Conservation and Recycling, Applied Geochemistry and ACS Sustainable Chemistry & Engineering. These journals represent the main scientific domains required for the topic: field contamination, geochemistry, radiological assessment, life-cycle assessment and environmental management.

2. PRODUCTION PATHWAYS AND WHY ENVIRONMENTAL IMPACTS OCCUR

REE production begins with a deposit, but the environmental risk profile is shaped by the full chain from exploration and land clearing to mining, beneficiation, hydrometallurgical extraction, solvent extraction, precipitation, calcination, waste storage and closure. Hard-rock deposits such as carbonatite-related ores may require blasting, crushing, grinding and flotation before acid or alkaline treatment. Heavy-mineral sands and monazite concentrates can be separated physically but may carry significant thorium. Ion-adsorption deposits in deeply weathered granitic terrains are different: REEs are adsorbed to clay surfaces rather than locked in resistant minerals, so ammonium sulfate or similar electrolytes can exchange ammonium for REEs in the field. This lower-temperature leaching route avoids some energy-intensive crushing, yet it creates a characteristic nitrogen-acidification signature.

Environmental impacts occur because REE extraction expands the reactive surface area of minerals, changes redox and pH conditions, introduces reagents, and generates waste streams that are chemically unlike the original ore body. A mineral that is stable underground may become reactive when crushed to fine particles and exposed to oxygenated water. A radionuclide-bearing mineral may be diluted in ore but concentrated in tailings or processing slimes. Ammonium salts that are useful for desorbing REEs from clays may become residual nitrogen pools that drive nitrification and acidification. Solvent extraction and precipitation steps can produce acidic or saline effluents. The same production chain can therefore generate physical disturbance, chemical mobilization and chronic exposure pathways.

Life-cycle assessment literature helps place these impacts in context. Studies by Sprecher et al. (2014), Vahidi et al. (2016), Arshi et al. (2018), Lee and Wen (2018), Bailey et al. (2020) and Schreiber et al. (2021) demonstrate that REE

supply chains can carry substantial upstream burdens, particularly when ore grades are low, reagent use is high, or waste treatment is weak. Life-cycle studies are not substitutes for site-specific field monitoring, but they reveal why environmental performance cannot be judged only by final product mass. A kilogram of separated oxide may represent many kilograms or tonnes of moved material, water, chemicals and residues. The useful lesson for thesis defence is that REE impacts are not a single pollutant problem; they are a system problem involving mineralogy, process design and waste governance.

Another reason impacts persist is that closure often begins after contamination pathways have already been created. Open pits, waste-rock piles, tailings impoundments, heap-leach areas and abandoned in-situ leaching fields can continue to interact with rainwater and groundwater. In humid monsoon climates, runoff and erosion can move contaminated fine particles into streams and rice paddies. In dry climates, wind erosion can transport dust. In both settings, tailings stability is central: physical failure releases bulk material, while chemical failure releases dissolved constituents. Kossoff et al. (2014) argue more broadly that mine tailings are long-term geochemical systems, not inert piles. That perspective is directly relevant to REE waste because residues may contain acidity, salts, metals and radionuclides.

Table 1. Standard Source-Pathway-Receptor Matrix for REE Environmental Impacts

Source	Mobilizing process	Transport pathway	Receptor	Typical indicators
Ion-adsorption clay leaching fields	Residual NH4+ nitrification, acid generation, cation exchange	Soil porewater, runoff, shallow groundwater	Topsoil, crops, streams, farmers	pH, NH4-N, NO3-N, exchangeable acidity, Al, Mn, REEs, Cd/Pb/As
Hard-rock waste rock and tailings	Weathering, acid or alkaline drainage, sulfide oxidation where present	Seepage, erosion, suspended sediment	Surface water, sediment, riparian soils	pH, sulfate, conductivity, Fe/Mn, trace metals, REEs
Monazite- or thorium-bearing residues	Radionuclide concentration, decay-chain redistribution	Gamma shine, radon, dust, seepage	Workers, nearby residents, biota	Dose rate, Th, U, Ra, radon, gross alpha/beta
Processing effluent and sludge	Acid/alkali use, solvent extraction loss, precipitation sludge	Wastewater discharge, sludge disposal, leaks	Water bodies, soils, treatment workers	COD/TOC where relevant, acidity, salts, fluorides, metals, REEs
Dust from roads, ore piles and dry tailings	Wind erosion and vehicle entrainment	Atmospheric deposition and ingestion/inhalation	Children, households, vegetation	PM, Pb, Cd, As, Th/U activity, enrichment factors

3. STANDARD ENVIRONMENTAL PATHWAY FRAMEWORK

The standard pathway framework begins by separating source, release mechanism, transport medium, exposure route and receptor. In REE mining, a source may be ore, waste rock, tailings, raffinate, sludge, leachate, dust or contaminated agricultural soil. Release mechanisms include mineral dissolution, cation exchange, nitrification, acid drainage, alkaline leaching, erosion, wind entrainment and dam seepage. Transport media include soil porewater, groundwater, surface runoff, suspended sediment, air and biological uptake. Receptors include microbial communities, plants, aquatic organisms, livestock, workers and residents. The framework is simple, but it prevents a common error: treating concentration alone as risk. Risk requires a complete pathway.

The framework also clarifies the difference between hazard and exposure. Thorium in a well-contained residue facility is a hazard requiring management, but the exposure pathway may be limited if the facility is engineered and monitored. Conversely, moderately contaminated dust on village roads may create a more immediate exposure pathway because children can ingest soil and dust repeatedly. Similarly, an acidic leaching field may not be a severe regional water-quality problem if drainage is collected and treated, but it can be a serious soil-reclamation problem if acidity, aluminum toxicity and nutrient imbalance prevent vegetation recovery. A thesis defence should therefore discuss environmental impacts in terms of linked mechanisms rather than isolated contaminants.

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The most important geochemical control in many REE settings is pH. A decrease in pH can increase the solubility of aluminum and manganese, weaken sorption of metals and REEs to clay and oxide surfaces, and change carbonate and sulfate complexation. Redox potential, organic matter, competing cations, phosphate, carbonate alkalinity and iron-manganese oxide surfaces also matter. For radionuclides, activity concentration, decay-chain equilibrium, particle size and radon emanation potential are important. For heavy metals, the environmentally relevant fraction may be exchangeable, carbonate-bound, reducible or oxidizable rather than total concentration alone. Sequential extraction methods can be useful, but they must be interpreted cautiously because operational fractions do not perfectly represent natural mineral hosts.

The framework can be applied at different scales. At the mine-lease scale, it guides monitoring points: upstream and downstream water, tailings seepage, reclaimed and unreclaimed soils, dust deposition zones and crop plots. At the catchment scale, it guides sediment tracing and cumulative-impact assessment. At the product-chain scale, it helps life-cycle analysts decide which emissions are site-specific and which can be generalized. For policy, the same framework supports licensing conditions, closure criteria and community health surveillance. It is therefore a practical bridge between field geochemistry and environmental management.

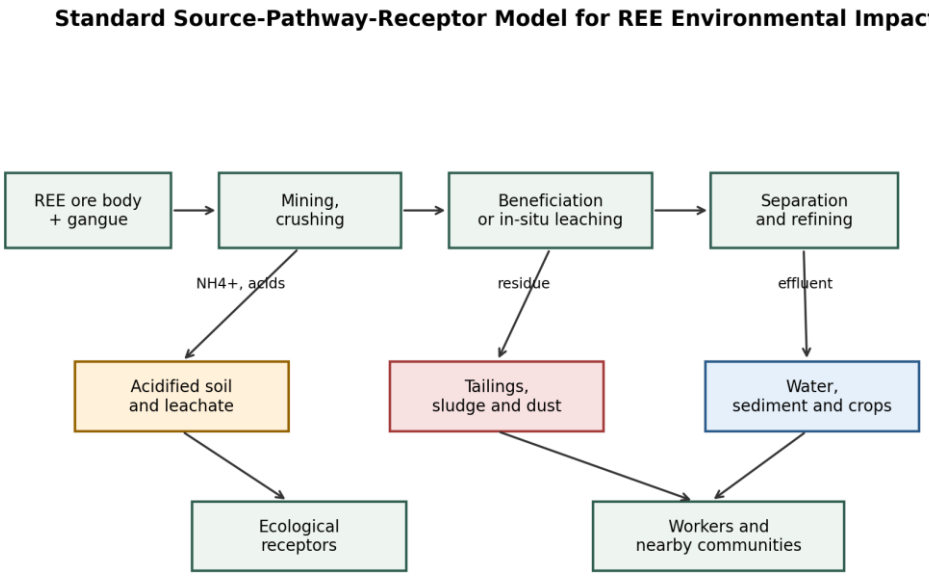


Figure 1. Pictorial demonstration of the standard REE source-pathway-receptor model.

4. SOIL ACIDIFICATION IN REE MINING AREAS

Soil acidification is especially associated with ion-adsorption REE mining, although acidification can also occur in hard-rock contexts where sulfide oxidation or acidic processing effluents are present. Ion-adsorption deposits are commonly developed in subtropical weathering profiles. REEs are weakly adsorbed onto clay minerals and iron-manganese oxides, allowing extraction by ion exchange. Ammonium sulfate leaching became attractive because ammonium ions can displace REE cations from exchange sites. Yet residual ammonium creates an environmental legacy. Once ammonium remains in soil, microbial nitrification can oxidize it to nitrate and release hydrogen ions. The resulting acidity lowers pH, alters exchangeable cations, mobilizes aluminum and manganese, and can increase the mobility of REEs and heavy metals.

Field evidence from Xu et al. (2023) provides one of the clearest demonstrations of this pathway. In a southeast China ion-adsorption rare earth tailing area, mined soils had lower pH than unmined soils, and the authors reported a decline of about 0.47 pH units per decade after mining, with hydrogen ion activity increasing strongly. They linked acidification to residual ammonium sulfate and nitrogen transformation, reporting elevated ammonium nitrogen and nitrate nitrogen in mined soils. The important point is that acidification was not merely a short-term reagent effect during extraction; it persisted as a soil-development problem after mining. This makes acidification a closure and reclamation issue, not only an operational issue.

Acidification has several consequences for soil quality. First, it can deplete base cations such as calcium, magnesium and potassium, reducing fertility and buffering capacity. Second, it can increase exchangeable aluminum, which is toxic to root growth and can limit revegetation. Third, acidification can change microbial communities and nitrogen cycling, reducing soil resilience. Fourth, lower pH can increase the desorption or dissolution of trace metals from clay minerals, organic matter and oxide surfaces. In practical terms, the same pH decline that damages soil fertility can also increase contaminant transport. This is why soil acidification should be evaluated together with heavy-metal mobility rather than as a purely agronomic issue.

A common misconception is that ion-adsorption mining is environmentally simple because it avoids large open pits and extensive crushing. In reality, in-situ or heap-style leaching can distribute chemical reagents through large volumes of weathered soil. If leachate collection is incomplete, the impacted volume may be broad and spatially heterogeneous. Patches of residual ammonium, acidity and mobilized metals can remain in the profile. Heavy rainfall can then move nitrate, sulfate, acidity and metals laterally or vertically. Because these deposits are often located in hilly, highly weathered landscapes, erosion and surface runoff may connect mined slopes to agricultural lowlands.

The acidification pathway also creates a feedback loop. As pH declines, metals and REEs become more mobile; as vegetation becomes stressed, erosion risk increases; as erosion removes organic-rich topsoil, buffering and recovery decline. Remediation therefore must address chemistry and physical land stability together. Liming alone may temporarily increase pH, but if residual ammonium remains and nitrification continues, acidity can reappear. Effective management requires reducing ammonium loading at the source, capturing leachate, recovering or replacing ammonium salts where feasible, controlling nitrification and nitrate transport, rebuilding organic matter, stabilizing slopes and monitoring pH over years rather than weeks.

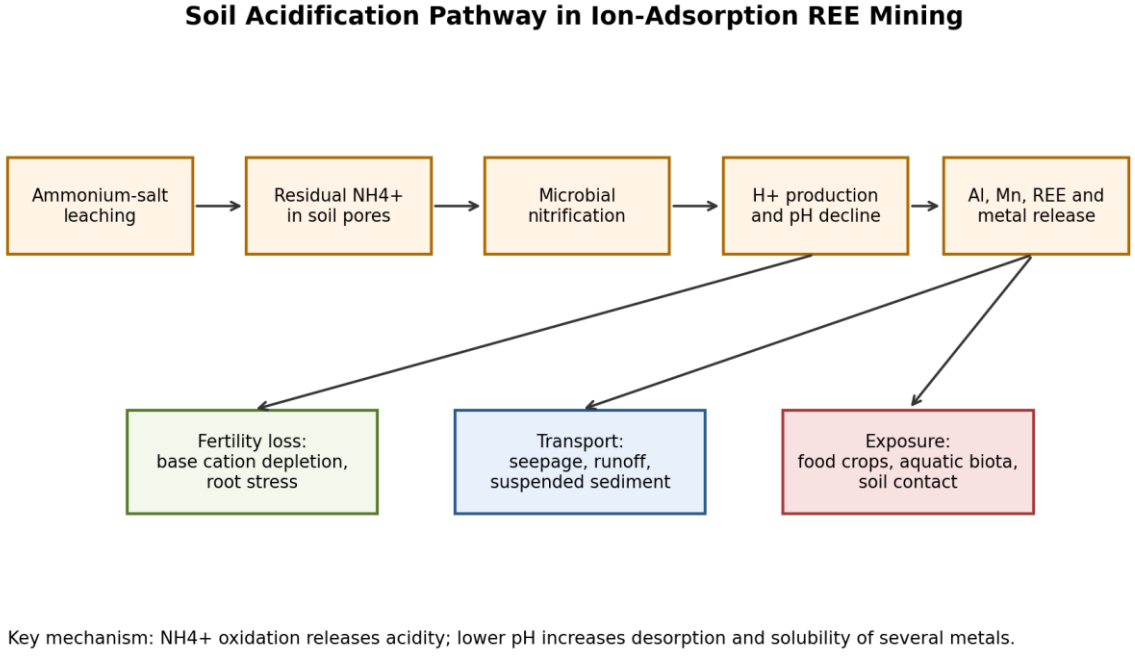


Figure 2. Soil acidification pathway driven by ammonium-salt leaching and nitrification.

5. RADIOACTIVE TAILINGS AND NATURALLY OCCURRING RADIOACTIVE MATERIAL

Radioactivity in REE production is primarily a naturally occurring radioactive material issue. Many REE minerals, especially monazite and xenotime, can contain thorium and uranium. Carbonatite and alkaline igneous systems may also carry radionuclides in accessory minerals. During mining and processing, radionuclides may be separated from REE products and concentrated in tailings, slimes or residues. The environmental problem is not simply the presence of thorium or uranium in the ore; it is the redistribution of long-lived radionuclides into waste streams that may have different physical and chemical behavior from the original mineral assemblage.

Radioactive tailings create several possible exposure pathways. External gamma radiation can affect workers or residents if tailings are poorly isolated or reused as construction material. Radon and thoron can emanate from residues depending on radium content, porosity, moisture and cover design. Fine particles can be inhaled or ingested as dust, carrying both radionuclides and metals. Seepage can transport dissolved uranium, radium or decay-chain products if geochemical conditions favor mobility. Erosion or dam failure can move contaminated solids into downstream sediment. Each pathway requires different monitoring: dose-rate surveys, radon measurements, dust sampling, radionuclide activity analysis, water chemistry and sediment assessment.

Li et al. (2016) provide field evidence that radiological assessment must be site-specific. Their in-situ gamma-ray survey of rare-earth tailings dams in Baotou and Bayan Obo examined spatial variation in radiation around major REE waste facilities. The value of such work is not only the reported dose-rate pattern but also the method: radiological risk should be mapped, measured and interpreted in relation to land use, distance, shielding and exposure time. A tailings dam does not create a uniform exposure field. Hotspots, access roads, uncovered surfaces and drainage channels can matter disproportionately.

Regulatory and technical reviews also emphasize decay-chain disruption. When ore is processed, thorium, uranium, radium and their decay products may be separated from each other, changing secular equilibrium. The U.S. Environmental Protection Agency review of REE production notes that thorium decay chains may be disrupted and that radium and radon mobility can become important in waste streams. This is a critical point for environmental management: measuring only total thorium or total uranium may not fully characterize radiological risk if radium, radon or daughter products are redistributed. Waste classification, worker protection and long-term storage design must therefore use radiological measurements appropriate to the residue.

The highest-risk scenarios are not inevitable. Engineered containment can reduce dust, radon, seepage and human access. Covers can provide shielding and limit water infiltration; liners and seepage collection can control water pathways; access control and land-use restrictions can prevent exposure; and long-term monitoring can detect changes in cover performance. However, the time scale of radionuclide hazards is long relative to mine life. Closure plans must therefore treat radioactive residues as a stewardship obligation extending beyond profitable extraction. A facility may be economically finished in decades, while thorium-bearing residues remain relevant for centuries or longer.

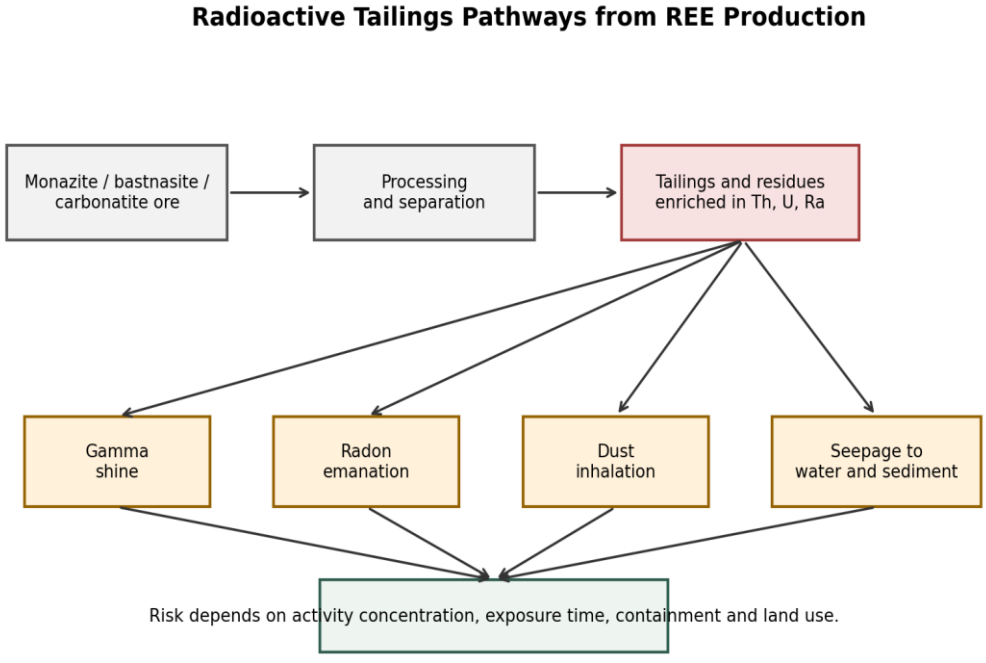


Figure 3. Radioactive tailings pathways associated with thorium-, uranium- and radium-bearing REE residues.

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6. HEAVY METALS, METALLOIDS AND CO-CONTAMINATION

Heavy-metal and metalloid contamination in REE mining areas reflects both natural geochemistry and processing disturbance. REE ores may contain lead, cadmium, arsenic, chromium, nickel, copper, zinc, manganese, barium and other elements in gangue minerals or accessory phases. Processing can mobilize these elements by crushing, acid leaching, alkaline treatment, flotation reagents, oxidation or changes in ionic strength. In ion-adsorption clay systems, acidification increases the probability that metals will desorb from soil exchange sites or dissolve from oxide phases. In hard-rock systems, sulfide oxidation, if present, can generate acidic drainage that dissolves metals from waste rock and tailings.

Liu et al. (2019) examined water, sediment and agricultural soil contamination from an ion-adsorption REE mining area and showed why cross-media assessment is essential. A mining impact may be missed if only mine soil is measured, because contaminants can move into streams, accumulate in sediment and reach agricultural land. Sediment often acts as both sink and secondary source: it records upstream contamination, but under changing pH, redox or flow conditions it can release metals back to the water column. Agricultural soils are especially important because they connect geochemistry to food-chain exposure.

Heavy metals are not all controlled by the same processes. Cadmium and zinc can be relatively mobile under acidic conditions. Lead may bind strongly to organic matter, phosphates and oxides but can still be transported in particulates or dust. Arsenic can behave differently depending on redox conditions and iron oxide stability. Chromium speciation controls toxicity and mobility. Manganese is sensitive to redox and pH and can become soluble in reduced or acidic conditions. Therefore, a monitoring program that reports only total metal concentrations is incomplete. It should include pH, redox-sensitive indicators, dissolved and particulate fractions, sediment grain size, organic matter and, where possible, bioavailable or operationally defined fractions.

Dust is a particularly direct exposure pathway for metals and radionuclides. Mine roads, ore storage, dry tailings beaches and processing residues can generate fine particles. These particles may enter homes, settle on crops or be inhaled by workers. Studies of road dust in REE mining regions, including work by Li et al. (2020), highlight that children can be important receptors because hand-to-mouth behavior increases soil and dust ingestion. The dust pathway is also socially visible: communities may experience it as nuisance, crop contamination and household contamination long before dissolved contaminants are measured downstream.

Co-contamination complicates ecological risk because mixtures can produce combined stress. Acidic soil, aluminum toxicity, cadmium uptake and nutrient deficiency may jointly reduce plant growth. Aquatic organisms may face low pH, suspended sediment and dissolved metals at the same time. Microbial communities may be affected by pH change, metal toxicity and altered nitrogen cycling. Risk assessment should therefore avoid treating each contaminant as isolated. A practical approach is to identify dominant stressor groups: acidity and nitrogen residues, heavy metals and metalloids, radionuclides, salinity and physical sediment load. Controls can then be matched to the dominant pathway while still monitoring mixture effects.

7. SOIL-WATER-SEDIMENT AND FOOD-CHAIN TRANSPORT

The movement of contaminants from REE operations into the wider environment often occurs through connected soil-water-sediment pathways. In humid areas, rainfall infiltrates mine soils and tailings, generating leachate that can move vertically to groundwater or laterally to streams. Overland flow can erode fine particles, especially from unvegetated slopes and tailings surfaces. Once particles enter channels, they may travel downstream during storm events and settle in slower-flowing reaches, reservoirs, irrigation channels or floodplains. Agricultural fields can be affected through irrigation water, overbank deposition, atmospheric dust deposition or direct placement of contaminated soil materials.

Sediment deserves special attention because it integrates contamination over time. Water samples provide snapshots and may miss episodic pulses, whereas sediment can store particle-bound REEs, metals and radionuclides. However, sediment also changes chemically. Reducing conditions can dissolve iron and manganese oxides, releasing sorbed elements. Acidic pulses can dissolve carbonates and desorb cations. Organic matter can complex metals and influence bioavailability. Therefore, sediment contamination should be interpreted together with hydrology and seasonal chemistry. In monsoon climates, the highest transport may occur during intense storms rather than average-flow conditions.

Food-chain transport depends on crop type, soil chemistry, irrigation water, plant physiology and contaminant form. REEs generally have limited plant uptake compared with essential nutrients, but uptake can occur and may increase under acidic conditions or in the presence of soluble complexes. Heavy metals such as cadmium are more established food-chain risks. Paddy systems require special attention because flooded conditions change redox chemistry, affecting arsenic, manganese, iron and other elements. If mining occurs near rice, vegetables or tea plantations, crop testing should be part of environmental management rather than an optional research exercise.

Human exposure pathways differ between workers and communities. Workers may experience inhalation of dust, direct contact with chemicals, external gamma exposure and accidental exposure to concentrated residues. Nearby residents may experience chronic lower-level exposure through dust deposition, drinking water, irrigated crops, fish, sediment contact and reuse of waste materials. Children, pregnant people and subsistence farmers may have higher vulnerability or exposure. These differences matter for monitoring design: occupational sampling, environmental sampling and public-health surveillance should not be collapsed into one generic program.

The pathway framework also helps identify practical intervention points. Source controls include reagent recovery, waste segregation, lined tailings, dust suppression and water recycling. Pathway controls include drainage collection, constructed wetlands or treatment systems where appropriate, erosion control, covers and sediment traps. Receptor controls include land-use planning, crop advisories, occupational protective equipment and community communication. The best strategy is normally to control the source first, because receptor controls alone can shift responsibility from operators to communities.

Table 2. Evidence and Citation Verification for Core Claims

Claim supported	Representative source	Journal/source quality	Why the citation is defensible
Ion-adsorption REE mining can cause persistent soil acidification through ammonium residues and nitrification.	Xu et al. (2023), DOI: 10.1016/j.scitotenv.2023.163834	Science of the Total Environment	Recent field study in a REE tailing area; reports pH, NH4-N, NO3-N and mining-age relationships.
Ion-adsorption mining can contaminate water, sediment and agricultural soils.	Liu et al. (2019), DOI: 10.1016/j.chemosphere.2018.10.109	Chemosphere	Cross-media field assessment directly matching soil-water-sediment pathway concerns.
REE tailings dams require direct radiological surveys because gamma dose is spatially variable.	Li et al. (2016), DOI: 10.1016/j.jenvrad.2015.10.027	Journal of Environmental Radioactivity	In-situ gamma-ray survey of Baotou and Bayan Obo rare-earth tailings dams.
Tailings are long-term geochemical systems with physical and chemical risk pathways.	Kossoff et al. (2014), DOI: 10.1016/j.apgeochem.2014.09.010	Applied Geochemistry	Widely cited review on mine tailings characteristics and environmental behavior.
REE separation and production can carry significant life-cycle burdens.	Sprecher et al. (2014), DOI: 10.1021/es404596q; Schreiber et al. (2021), DOI: 10.1016/j.scitotenv.2021.148257	Environmental Science & Technology; Science of the Total Environment	High-impact LCA literature linking process design, energy and emissions to REE supply chains.
Radiological waste from REE production requires attention to Th/U series, radium and radon.	EPA (2012) technical review; Li et al. (2016)	Regulatory technical review plus peer-reviewed field evidence	Combines regulatory waste-pathway analysis with site-based measurement.

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8. EVIDENCE SYNTHESIS BY PATHWAY

The soil acidification evidence is strongest for ion-adsorption deposits because the mechanism is well defined and field data support it. Ammonium sulfate leaching leaves nitrogen residues; nitrification generates acidity; pH decline changes soil chemistry; and field measurements show lower pH and elevated nitrogen species in mined areas. The uncertainty is not whether the pathway exists, but how severe it becomes under specific operational and climatic conditions. Important modifiers include leachant dose, recovery efficiency, soil buffering capacity, rainfall, drainage design, microbial activity, slope stability and reclamation practice.

The radioactive tailings evidence is strongest for thorium-bearing mineral systems and residue facilities where radionuclides become concentrated. The pathway is scientifically well established because thorium and uranium decay chains are known, and field surveys can measure gamma dose rates and radionuclide activities. The uncertainty lies in exposure: whether radionuclides are isolated, whether radon can accumulate, whether dust reaches residents, whether seepage occurs and whether land use changes after closure. A defensible thesis argument should therefore state that radiological risk is deposit- and management-specific, not uniform across all REE operations.

The heavy-metal evidence is broad but more heterogeneous. Many studies show elevated metals in soils, sediments, waters or dust near REE operations, but the dominant elements vary by deposit, processing history and local geology. This heterogeneity is expected. A bastnasite deposit, a monazite-bearing sand and an ion-adsorption clay field do not have the same mineral hosts or reagents. The generalizable pathway is disturbance plus geochemical mobilization, while the specific metal signature must be measured locally. This is why baseline studies before mining are essential. Without baseline data, it is difficult to distinguish mining impact from naturally high geochemical background.

Across pathways, the most important methodological lesson is to pair total concentration with mobility and exposure metrics. For soil acidification, pH and exchangeable acidity are as important as total REE concentration. For radioactive residues, dose rate, radionuclide activity and radon potential are more relevant than total tailings mass. For heavy metals, dissolved fractions, bioavailable fractions, dust loading and crop concentrations can be more meaningful than total soil concentration alone. Environmental impact assessment should therefore be designed around decisions: whether water is safe, whether crops are safe, whether tailings need stronger containment, whether reclamation is succeeding and whether workers or communities require exposure reduction.

A second synthesis point is that impacts can be reduced substantially by process design. Cleaner leaching systems, reagent recycling, closed water loops, residue neutralization, tailings covers, dust control, radiological segregation and progressive reclamation are not speculative ideas. They are standard environmental-management principles. The challenge is implementation quality, regulatory enforcement and long-term financing. REE demand will likely grow with clean-energy deployment, so the key question is not whether REEs should exist in technology supply chains. The key question is how to produce and recycle them with environmental controls that match their strategic importance.

9. MANAGEMENT AND REMEDIATION STRATEGIES

Management should begin before mining with mineralogical characterization, baseline environmental monitoring and pathway-specific risk assessment. Mineralogy identifies whether thorium-, uranium-, sulfide- or metal-bearing phases are present. Baseline soil, water, sediment, dust and crop data establish natural background. Hydrological assessment identifies likely drainage pathways and flood risk. Social baseline studies identify nearby receptors, water uses, agricultural systems and vulnerable populations. Without these data, later claims of compliance or harm become difficult to evaluate.

For soil acidification, prevention is better than post-closure correction. Operators should minimize ammonium-salt losses, collect and recycle leachate, avoid uncontrolled in-situ injection, and monitor ammonium, nitrate, sulfate and pH throughout the profile. Where acidification has occurred, liming can improve pH, but it should be paired with nitrogen management, organic amendment, revegetation and erosion control. Biochar, compost and phosphate amendments may help immobilize some metals, but their performance depends on local soil chemistry and should be tested before large-scale application. Reclamation success should be measured using pH recovery, vegetation establishment, runoff quality and metal mobility, not surface appearance alone.

For radioactive tailings, management requires segregation, engineered containment and radiological monitoring. Residues with elevated activity should not be mixed casually with ordinary waste because dilution can make monitoring harder and expand contaminated volumes. Tailings facilities should include covers or water management systems that limit dust and radon, seepage controls, access restrictions and long-term stability design. Monitoring should include external dose rates, radionuclide activities in tailings and nearby soils, radon where relevant, and water or sediment sampling around seepage and drainage points. Emergency planning should consider extreme rainfall and dam stability because physical release of tailings can create widespread contamination.

For heavy metals, source control and geochemical stabilization are central. Acid drainage prevention, pH control, oxidation management, water treatment and sediment control can reduce metal release. In contaminated soils, remediation may include excavation for hotspots, stabilization with lime, phosphate or iron amendments, phytostabilization, soil washing in limited cases, and land-use restrictions. Phytoremediation is often attractive in concept but slow and uncertain for mixed contamination; it is better understood as a complementary tool for stabilization and revegetation rather than a universal solution. Crop monitoring and food-chain risk assessment are necessary when agriculture occurs near mining zones.

Governance is as important as technology. Environmental controls fail when closure funds are absent, monitoring stops too early, illegal mining bypasses formal systems, or communities lack access to data. A credible management plan should include public reporting, independent auditing, financial assurance for closure, grievance mechanisms and adaptive management triggers. If pH decline, dose rate, seepage chemistry or crop contamination exceeds agreed thresholds, operations should adjust rather than wait for annual reports. Because REE supply chains are global, downstream manufacturers and purchasers can also influence performance through responsible sourcing requirements and recycling investments.

Table 3. Pathway-Specific Controls and Monitoring Indicators

Pathway	Priority controls	Monitoring indicators	Residual risk if controls fail
Soil acidification	Reagent recovery; closed leachate collection; pH buffering; nitrogen management; revegetation	pH, exchangeable acidity, NH4-N, NO3-N, sulfate, Al/Mn, vegetation cover	Long-term fertility loss, metal mobility, erosion and crop uptake
Radioactive tailings	Waste segregation; lined and covered storage; dust suppression; radon and seepage control; access restriction	Gamma dose rate, Th/U/Ra activity, radon, dust activity, seepage chemistry	External exposure, inhalation, contaminated sediment and long-term land-use restriction
Heavy metals	Acid drainage prevention; water treatment; sediment traps; stabilization amendments; dust control	Dissolved and total metals, sediment metals, bioavailable fractions, dust loading, crop metals	Water-quality impairment, food-chain exposure and ecological toxicity
Dust and particulate transport	Road watering or paving; enclosure; progressive cover; speed limits; windbreaks	PM, deposited dust, metal concentrations, radionuclide activity, household dust	Inhalation, ingestion, crop surface contamination and community nuisance
Post-closure migration	Long-term covers; drainage maintenance; financial assurance; land-use controls	Cover integrity, seepage, downstream sediment, vegetation, groundwater	Delayed contaminant release after operators leave

10. POLICY AND RESEARCH RECOMMENDATIONS

First, environmental impact assessment for REE projects should be deposit-specific. A generic REE permit is inadequate because ion-adsorption clays, monazite-bearing sands and carbonatites present different dominant risks. Permitting should require mineralogical and radiological characterization before mine approval, including thorium, uranium, radium and

relevant heavy metals. It should also require acid-base accounting or equivalent geochemical tests where sulfides or acidic processing residues are possible. For ion-adsorption deposits, nitrogen mass balance should be a formal part of the environmental assessment.

Second, monitoring should be pathway-based and transparent. Standard monitoring suites should include upstream and downstream water quality, soil pH and metal mobility, sediment chemistry, dust deposition, crop testing where relevant and radiological measurements for radionuclide-bearing deposits. Data should be reported in forms useful to communities, not only regulators. For example, a map of dose-rate measurements or pH recovery zones is more understandable than a table of compliance codes. Transparency also builds trust in strategic mineral supply chains.

Third, research should focus on long-term field performance. Many remediation methods perform well in laboratory columns or short-term plots but are less tested under monsoon rainfall, freeze-thaw cycles, vegetation succession, informal land use and decades of cover aging. Long-term studies of reclaimed ion-adsorption mining areas are especially needed to determine whether pH recovery is stable and whether residual nitrogen continues to generate acidity. Similarly, long-term monitoring of REE tailings covers is needed to evaluate dust suppression, radon control and seepage chemistry.

Fourth, recycling and circular economy strategies should be treated as environmental controls as well as resource strategies. Recycling magnets, phosphors and industrial scrap can reduce pressure on primary mining, although recycling has its own chemical and energy requirements. Life-cycle assessments suggest that secondary supply can reduce some burdens, but only if collection, separation and processing are efficient. Policy should support product design for recycling, traceability of REE-containing components and responsible waste management for end-of-life electronics and magnets.

Finally, research should integrate environmental justice. Many REE impacts occur in mining regions that do not receive the full benefit of downstream clean-energy technologies. Communities may bear land disturbance, dust, water pollution and long-term waste risks while value is captured elsewhere. Responsible REE supply therefore requires more than technical mitigation. It requires fair consultation, compensation, monitoring access and post-closure accountability. A thesis defence can frame this as a central sustainability challenge: the materials of energy transition must not reproduce sacrifice-zone patterns at the front end of the supply chain.

Table 4. Deposit and Process Settings Versus Dominant Environmental Concerns

Setting	Typical extraction/process feature	Dominant concerns	Recommended emphasis
Ion-adsorption clay deposits	Ammonium-salt exchange leaching in weathered soils	Soil acidification, nitrogen residues, metal mobility, erosion	Nitrogen mass balance, pH recovery, leachate capture, agricultural soil monitoring
Monazite-bearing heavy mineral sands	Physical concentration followed by chemical cracking	Thorium-bearing residues, gamma exposure, dust	Radiological segregation, residue containment, dose and radon monitoring
Carbonatite/hard-rock REE deposits	Mining, crushing, flotation, acid or alkaline processing	Tailings volume, reagents, metals, radionuclides where present	Tailings geochemistry, water treatment, dust and seepage control
Informal or legacy mining areas	Uncontrolled excavation, poor closure, unmanaged waste	Diffuse contamination, abandoned acidified soils, uncertain exposure	Baseline reconstruction, hotspot mapping, community risk communication
Recycling and secondary supply	Magnet, phosphor or scrap processing	Chemical handling, process effluent, worker exposure	Closed-loop chemistry, waste minimization, product stewardship

11. SAMPLING, ANALYTICAL QUALITY AND INTERPRETATION

A strong environmental review must be clear about how evidence is produced. Sampling design is often the difference between a defensible conclusion and a misleading claim. In REE mining areas, samples should represent both spatial gradients and pathway logic. For soil, this means sampling reclaimed and unreclaimed mine surfaces, downslope

agricultural soils, reference soils outside the affected catchment, and depth profiles where leaching is expected. For water, this means upstream controls, discharge points, drainage channels, groundwater wells and downstream receiving waters during both dry and wet seasons. For sediment, it means depositional zones, fine fractions and sites upstream and downstream of mine influence. For dust, it means source areas, roads, residential deposition zones and indoor dust where community exposure is a concern.

Analytical quality is especially important because REE concentrations can be affected by digestion method and matrix effects. Total digestion using strong acid mixtures may estimate near-total concentrations, while weaker extraction may better approximate environmentally mobile fractions. Neither result is automatically superior; the correct method depends on the question. If the question is total inventory in tailings, strong digestion is appropriate. If the question is plant availability or leaching risk, exchangeable or dilute-acid fractions may be more relevant. For radionuclides, gamma spectrometry, alpha spectrometry or mass spectrometry may be selected depending on isotopes and detection limits. For pH and nitrogen, sample storage and timing matter because microbial transformations continue after collection.

Quality assurance should include blanks, duplicates, certified reference materials, detection limits and clear reporting of units. This sounds procedural, but it directly affects interpretation. A claim that cadmium exceeds a guideline is not meaningful if digestion recovery is unknown or if background soils naturally contain elevated cadmium. A claim that REEs are enriched in crop tissues needs plant washing protocols, dry-weight basis and comparison with control crops. A claim that a tailings facility presents radiological risk needs dose-rate context, occupancy assumptions and radionuclide activity data. High-impact journals usually require these details, which is one reason peer-reviewed evidence is preferable to unsupported reports or news accounts.

Another interpretive issue is background correction. Many REE deposits occur in geologically unusual terrains, so surrounding soils may naturally contain higher REEs, thorium, uranium or metals than regional averages. Baseline studies before mining are therefore indispensable. Where pre-mining data do not exist, researchers may use upstream sites, nearby unmined catchments, deep soil horizons or regional geochemical maps as references. Each approach has uncertainty. The most defensible interpretation combines multiple lines of evidence: concentration gradients away from the source, enrichment factors, isotopic or mineralogical signatures, land-use history, hydrological connectivity and temporal patterns after mining begins.

Risk assessment also requires careful use of standards. Soil guideline values differ by country, land use and exposure assumptions. Agricultural soil standards are not the same as industrial land standards. Drinking-water limits are not the same as irrigation-water recommendations. Radiological dose limits require assumptions about time spent at a location, shielding, ingestion and inhalation. Therefore, the review should avoid treating one threshold as universal. Instead, standards should be used as screening tools that trigger more detailed investigation. This is particularly important for REE mining because communities may face combined exposure to acidity, metals, dust and radionuclides rather than a single contaminant at a single point.

For thesis work, the most persuasive evidence chain is triangulated. A pathway is strongest when process knowledge, field measurements and receptor evidence align. For example, ammonium leaching plus residual NH4-N and NO3-N plus declining pH plus increased mobile Al or metals forms a coherent acidification chain. Thorium-bearing ore plus elevated activity in residues plus gamma dose-rate hotspots plus dust or access pathways forms a coherent radiological chain. Elevated metals in mine soil plus downstream sediment enrichment plus crop uptake or dust ingestion estimates forms a coherent heavy-metal chain. This review therefore treats individual studies as parts of pathway evidence rather than isolated facts.

12. INTEGRATED DISCUSSION FOR A THESIS DEFENCE

A useful defence argument can begin with the statement that REE impacts are governed by geochemical transformation. Mining does not create elements such as thorium, cadmium or lanthanum; it changes their concentration, mineral host, particle size, chemical environment and proximity to people. This framing is scientifically precise and avoids exaggeration. It also explains why the same element can be low risk in one setting and high risk in another. Thorium inside resistant monazite grains buried in an ore body behaves differently from thorium-rich residue in a dry, uncovered tailings facility. Cadmium bound in a stable mineral behaves differently from cadmium in an acidified soil solution. Ammonium in a controlled reagent loop behaves differently from residual ammonium left in a leached hillslope.

A second defence point is that the three focus areas are connected by pH and particle transport. Soil acidification is not just one impact among many; it is a driver that can intensify heavy-metal mobility and weaken revegetation. Tailings are not just storage facilities; they are sources of fine particles, leachate and, in some deposits, radionuclide exposure. Heavy metals are not only dissolved pollutants; they can move as dust, sediment, colloids and crop contaminants. This systems view helps examiners see that the review is not a list of hazards. It is a mechanistic synthesis of how hazards become environmental impacts.

A third point is that high-impact literature supports both concern and solution. Science of the Total Environment, Chemosphere and Journal of Environmental Radioactivity provide field evidence for acidification, cross-media contamination and radiological surveying. Environmental Science & Technology, Nature Sustainability, Resources Conservation and Recycling and ACS Sustainable Chemistry & Engineering provide life-cycle and supply-chain perspectives. Applied Geochemistry and Journal of Hazardous Materials contribute waste and remediation insight. Together, these sources justify the review's conclusions without relying on sensational claims. They also show that environmental performance is variable: better process design and governance can reduce impacts, while poor controls can create persistent contamination.

The review also has a policy implication that is important for modern resource debates. Clean-energy technologies can shift environmental burdens upstream if mineral supply chains are not responsibly managed. This does not mean wind turbines, electric vehicles or efficient electronics are environmentally invalid. It means their material supply chains must meet the same sustainability expectations that the technologies themselves claim to support. REE mining should therefore be evaluated using full-chain thinking: mining, processing, waste, worker safety, community exposure, recycling and product design. The environmental credibility of the energy transition depends partly on whether strategic minerals are extracted with high environmental standards.

For soil acidification, the thesis defence should emphasize measurable indicators. Examiners may ask how acidification is proven. The answer is not simply that ammonium sulfate was used. Evidence includes lower pH in mined soils, elevated ammonium and nitrate, pH decline with mining age, exchangeable acidity, aluminum mobilization, base-cation depletion and comparison with unmined reference soils. Xu et al. (2023) is valuable because it links several of these indicators in a field setting. A robust monitoring plan would track these variables over time and depth, particularly because surface pH alone can miss acidity stored deeper in the weathering profile.

For radioactive tailings, the defence should emphasize that radioactivity is a normal geological feature of some REE ores but becomes a management issue when concentrated in waste. Questions may arise about whether all REE mines are radioactive hazards. The accurate answer is no: risk varies by mineralogy, radionuclide activity, residue handling and exposure pathway. However, where monazite, xenotime, thorium-bearing carbonatites or concentrated residues are present, radiological characterization is essential. Li et al. (2016) is useful because it demonstrates field measurement around major tailings dams rather than relying on theoretical concern. The EPA review is useful because it explains process-related redistribution of decay-chain radionuclides.

For heavy metals, the defence should avoid overgeneralization. Not every REE mine releases the same metals, and total concentration does not always equal bioavailable risk. The stronger argument is that REE operations can mobilize co-occurring metals through disturbance, acidification, drainage and dust, and therefore require site-specific metals assessment. Liu et al. (2019) is useful because it connects water, sediment and agricultural soil rather than treating one medium alone. Road-dust studies add a community-exposure dimension, especially for children. The result is a clear monitoring recommendation: soil, water, sediment, dust and crops should be studied together where communities or farms are nearby.

The remediation discussion should also be realistic. There is no single technology that fixes all REE environmental impacts. Liming may improve acidified soils but does not remove radionuclides. Tailings covers may reduce dust and radon but require maintenance. Water treatment can remove metals but generates sludge that must be managed. Phytoremediation may stabilize surfaces but is slow for deep or highly contaminated materials. Recycling can reduce primary mining pressure but cannot immediately satisfy all demand. A credible management strategy is therefore layered: prevent contamination first, contain unavoidable residues, monitor pathways, remediate hotspots, and maintain accountability after closure.

Finally, the review should identify knowledge gaps without weakening its conclusions. More long-term data are needed on reclaimed ion-adsorption mining soils, especially the persistence of nitrogen-driven acidification. More field evidence is needed on crop uptake under mixed REE-metal contamination. More site-specific radiological studies are needed outside the best-known Chinese mining districts. More life-cycle assessments are needed using primary data from newer operations and recycling routes. These gaps do not mean the current evidence is insufficient to act. They mean environmental management should be adaptive, with monitoring results used to update controls as mines operate and close.

13. CASE-STYLE SCENARIOS AND EXAMINER-READY INTERPRETATION

Scenario one is an ion-adsorption clay mine on a humid, agricultural hillside. The main environmental concern is not a large radioactive tailings dam but a chemically altered soil profile. Ammonium sulfate or a similar leachant is introduced to exchange REEs from clay surfaces, and incomplete recovery leaves ammonium in porewater and exchange sites. Over time, nitrification converts ammonium to nitrate and releases hydrogen ions. Rainfall then moves nitrate, sulfate, acidity and mobilized metals downslope. The expected field signal is lower pH in mined soils, elevated mineral nitrogen, increased exchangeable aluminum or manganese, reduced vegetation cover, and possible enrichment of metals or REEs in runoff sediment. The management response should focus on leachate collection, nitrogen recovery, pH correction, erosion control and agricultural monitoring.

Scenario two is a monazite-bearing concentrate processed near a coastal or inland separation plant. Here, the critical issue is not necessarily soil acidification but radioactive residue management. Monazite commonly contains thorium, and processing can separate REEs from thorium-rich residues. If residues are stored dry and uncovered, dust and gamma exposure may become important. If stored wet without strong containment, seepage can become important. The field investigation should include radionuclide activity in residues, external dose-rate mapping, radon or thoron potential where relevant, dust sampling and water monitoring around storage areas. The correct interpretation is that radioactivity is mineralogically expected, but exposure depends on engineering and land use.

Scenario three is a hard-rock carbonatite or alkaline complex with large-volume tailings. The environmental profile combines conventional mine-waste issues with REE-specific concerns. Crushing and flotation produce fine tailings; reagents and process water create wastewater-management needs; accessory minerals may carry thorium, uranium, fluorine or heavy metals; and tailings dams create both geochemical and physical stability risks. The expected monitoring suite is broad: pH, conductivity, sulfate, fluoride where relevant, dissolved metals, REEs, radionuclide activity, seepage flows, dust, dam stability and downstream sediment. The strongest management response is integrated tailings design with water balance, geochemical prediction, cover planning and closure finance from the beginning of the project.

Scenario four is an abandoned or informal mining area. These sites are often the hardest to interpret because there may be no baseline data, poor records of reagent use and multiple small disturbance zones. Contamination may appear as patchy acidified soil, eroded gullies, contaminated stream sediment, waste piles or household dust. The first task is mapping: identify sources, flow paths, land use and community exposure points. The second task is prioritization: locate hotspots that create complete exposure pathways. The third task is stabilization: stop erosion, restrict access to dangerous residues, treat or divert contaminated drainage and restore vegetation. For a thesis, this scenario is useful because it shows why governance and enforcement are environmental controls, not administrative details.

Scenario five is a proposed new REE project seeking approval under modern sustainability expectations. The project should be assessed against a prevention hierarchy. Can reagent use be reduced or recycled? Can ore sorting reduce tailings volume? Can radionuclide-bearing streams be separated early? Can process water be closed-loop? Can tailings be filtered, covered or placed in a more stable form? Can real-time pH, conductivity and flow monitoring detect leaks quickly? Can communities access monitoring results? These questions translate the review into design criteria. They also connect environmental science with decision-making, which is important in a defence because the examiner may ask how the review informs practice.

Scenario six is a circular-economy pathway based on magnet or phosphor recycling. Recycling can reduce pressure on primary mining, but it does not eliminate environmental assessment. Secondary processing may use acids, solvents, roasting, molten salts or electrochemical methods, and residues still require management. The advantage is that secondary

feedstocks may contain higher target-metal concentrations than ores, potentially reducing material movement. The risk is that recycling facilities can create their own waste streams if chemical recovery is inefficient. A balanced thesis answer is that recycling is a necessary complement to responsible mining, not an automatic substitute. Its environmental value depends on collection efficiency, process chemistry, energy source and waste control.

These scenarios show how the same three pathway themes can be adapted to different REE settings. Soil acidification dominates where ammonium leaching changes weathered soils. Radioactive tailings dominate where thorium- and uranium-bearing minerals are concentrated in residues. Heavy metals dominate where ore gangue, acidic conditions, dust or sediment transport create exposure. The examiner-ready conclusion is that REE environmental impact assessment should begin with deposit type and process design, then trace complete pathways to receptors. That structure is more scientifically defensible than making broad statements that all REE mining is either catastrophic or harmless.

14. LIMITATIONS AND FUTURE RESEARCH NEEDS

This review is limited by the uneven geography of available evidence. A large share of field literature comes from China, especially ion-adsorption REE districts and the Baotou-Bayan Obo region. That literature is highly relevant because these areas have been central to global REE production, but it cannot represent every deposit, climate or regulatory setting. Emerging projects in Africa, Europe, North America, Australia and Southeast Asia may have different ore grades, mineral hosts, waste practices and community exposure patterns. Future research should therefore expand comparable field studies across newer REE provinces before production scales up.

A second limitation is that many studies measure contamination at one point in time. REE impacts can be episodic and seasonal: storm runoff, tailings seepage, dry-season dust and post-closure changes may not be captured by a single sampling campaign. Longitudinal studies are needed to understand whether reclaimed soils continue to acidify, whether tailings covers remain effective, and whether downstream sediments act as long-term secondary sources. Monitoring programs should be designed to capture wet-season pulses and dry-season dust, because average annual conditions may underestimate actual exposure.

A third research need is better linkage between geochemical measurements and biological outcomes. Many papers report total REEs, metals or radionuclides, but fewer connect these measurements to microbial function, crop uptake, aquatic toxicity, human exposure biomarkers or ecosystem recovery. Future work should combine chemistry with ecotoxicology and public-health assessment, especially in agricultural landscapes. This does not require every study to become a health study, but it does require clearer translation from concentration to ecological or human relevance.

Finally, future research should improve comparison between primary mining and recycling. Recycling is often promoted as the cleaner pathway, but its benefits depend on collection systems, separation efficiency, chemical inputs, energy supply and waste controls. Standardized life-cycle inventories using primary operational data would help compare mining, reprocessing of tailings, magnet recycling and alternative product designs. Such work would allow policymakers and manufacturers to choose strategies that reduce total environmental burden rather than shifting it from one location or life-cycle stage to another.

15. CONCLUSION

Rare earth elements are not environmentally benign simply because they enable low-carbon technologies. Their production can generate serious local impacts through soil acidification, radioactive tailings and heavy-metal contamination. The strongest thesis-level conclusion is that these impacts follow recognizable pathways. In ion-adsorption clay mining, ammonium-salt leaching can leave residual nitrogen that nitrifies and acidifies soil, reducing fertility and mobilizing metals. In thorium- or uranium-bearing deposits, processing can concentrate naturally occurring radionuclides into tailings and residues that require radiological controls. In many deposit types, heavy metals and metalloids can be mobilized by acidification, weathering, dust and sediment transport.

The practical implication is that REE environmental management should be pathway-specific, measured and long-term. Source controls should reduce reagent loss, waste generation and radionuclide dispersion. Pathway controls should contain seepage, dust, erosion and sediment movement. Receptor controls should protect workers, residents, crops and aquatic ecosystems. High-impact literature supports these conclusions, but it also shows that risks vary by deposit type,

process design, climate and governance. Therefore, the best environmental assessment is neither a blanket condemnation nor a blanket reassurance. It is a disciplined evaluation of sources, pathways, receptors and controls.

For a thesis defence, the key message can be stated plainly: REEs are strategically important, but strategic importance does not reduce environmental responsibility. Clean-energy supply chains are only credible if the upstream mining and processing systems are also made cleaner. Soil pH, nitrogen residues, thorium and uranium series radionuclides, heavy metals, dust, leachate and tailings stability should be treated as core design variables. When these variables are monitored and controlled, REE production can be improved. When they are ignored, the environmental costs are transferred to soils, waters and communities.

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