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Critical mineral mining and environmental sustainability: Impacts, challenges, and pathways for responsible resource development

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ABSTRACT

The accelerating global transition toward low-carbon energy systems has substantially increased demand for critical minerals, including lithium, cobalt, nickel, copper, and rare earth elements. These minerals are essential for renewable energy technologies, electric mobility, and advanced industrial applications. However, their extraction and processing generate significant environmental and socio-ecological challenges. This review adopts a structured narrative synthesis approach to critically evaluate the environmental impacts of critical mineral development across major producing regions worldwide. Key issues include land degradation, deforestation, water depletion and contamination, greenhouse gas emissions, air pollution, and biodiversity loss, particularly in ecologically sensitive and water-stressed regions. The analysis further highlights how these impacts are often unevenly distributed, disproportionately affecting local communities, Indigenous populations, and environmentally vulnerable areas. Beyond environmental risks, the review examines governance challenges, supply-chain inequities, and the growing sustainability paradox in which minerals required for decarbonization may themselves be produced through environmentally intensive pathways. Emerging mitigation strategies, including circular-economy models, recycling, material efficiency, cleaner extraction technologies, and transparent ESG-based governance frameworks, are critically assessed for their potential to reduce environmental footprints and enhance resource security.

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1. Introduction

The global pursuit of a low-carbon future has triggered an unprecedented transformation in energy systems, placing critical minerals at the centre of technological and economic change. Minerals such as lithium, cobalt, nickel, copper, and rare earth elements are indispensable for renewable energy infrastructure, electric vehicles, and advanced digital technologies, making them foundational to the sustainable energy transition (International Energy Agency [IEA], 2024a; Reich and Simon, 2025). As nations accelerate decarbonization efforts under international climate commitments, demand for these minerals is projected to increase multiple-fold over the coming decades, reshaping global resource dynamics and supply chains (IEA, 2024a; Sovacool et al., 2020). Underlying this optimistic narrative is a complex and often underexamined reality". This rephrase may help sound more like an academic publishing journal. The extraction and processing of critical minerals while enabling clean energy technologies can generate significant environmental and socio-ecological impacts. This duality has led many scholars to describe the phenomenon as the "environmental paradox" of the energy transition, wherein technologies intended to mitigate climate change may simultaneously intensify pressures on land, Water resources, and ecosystems (Ali et al., 2017; Lèbre et al., 2020). Mining activities are frequently encroaching on ecologically sensi-

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tive regions and developing economies, where governance challenges and limited regulatory capacity can exacerbate environmental degradation and social inequalities (World Bank, 2020; Owen et al., 2023).

Recent studies have highlighted that critical mineral extraction is associated with a wide spectrum of environmental impacts, including extensive land transformation, deforestation, water scarcity, contamination from acid mine drainage, air pollution from smelting operations, and significant biodiversity loss (Mudd, 2023; Rodríguez et al., 2023; Mousavinezhad et al., 2024). For instance, lithium extraction in arid regions has been linked to groundwater depletion and ecosystem stress, while cobalt mining has raised concerns over both environmental contamination and public health risks in mining communities (Banza Lubaba Nkulu et al., 2018; Lakshman, 2024). Similarly, rare earth element processing involves chemically intensive techniques that generate hazardous waste, posing long-term ecological risks (Dutta et al., 2016; Ikeh, 2025). Beyond environmental implications, the expansion of critical mineral supply chains has brought renewed attention to socio-economic and ethical dimensions. Indigenous communities and local populations are often vulnerable to displacement, livelihood loss, and the unequal distribution of economic benefits, underscoring the urgent need for inclusive and equitable governance frameworks (Lèbre et al., 2020; Kumar, 2024).

In response to these challenges, a growing body of research emphasises the importance of adopting integrated approaches that combine environmental stewardship, technological innovation, and policy reform. Circular economy strategies, such as recycling, material substitution, and resource efficiency, are increasingly recognised as essential pathways to reduce dependence on primary extraction (Hossain and Sahajwalla, 2024; Shimizu and Owada, 2024). Concurrently, emerging technologies, including bioleaching and direct lithium extraction, offer promising opportunities to minimise environmental impacts (Dutta et al., 2016; Arshad et al., 2025). Policy initiatives at both national and international levels are also evolving to promote sustainable supply chains, transparency, and environmental accountability (Ragonnaud, 2023; Kotarska and Young, 2023). Despite these advancements, significant gaps remain in understanding the cumulative and long-term impacts of critical mineral extraction, particularly amid rapidly rising global demand. There is a pressing need for interdisciplinary research, robust environmental monitoring, and stronger governance mechanisms to ensure that the clean energy transition proceeds in a manner that safeguards ecological integrity and promotes social justice (Owen et al., 2023; Sovacool et al., 2020).

The present review aims to provide a comprehensive and critical synthesis of the environmental impacts of critical mineral extraction, while evaluating emerging strategies to achieve a more sustainable and equitable energy transition. By bridging environmental science, resource governance, and technological innovation, this study seeks to contribute to a more holistic understanding of how critical minerals can support rather than undermine global sustainability goals. The figures presented in this review are conceptual representations synthesised from existing literature to provide a holistic understanding of critical mineral sustainability. The interconnections among critical mineral demand, environmental impacts, and sustainability pathways are schematically illustrated in Fig. 1.

2. Methodology

The present study adopts a structured narrative review approach to critically synthesise the environmental, socio-economic, technological, and governance dimensions of critical mineral extraction and associated sustainability pathways. Relevant literature was collected from major scientific databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, as well as authoritative reports from the International Energy Agency (IEA), World Bank, European Commission, UNEP, and USGS. Publications from 2010 to 2026 were prioritised to capture both foundational developments and recent advances in the rapidly evolving critical minerals sector. The selected literature was thematically organised into key areas, including land degradation, water stress, atmospheric emissions, biodiversity loss, socio-environmental governance, and sustainable mitigation strategies. Comparative thematic synthesis and critical interpretation were then applied to identify global trends, regional disparities, emerging solutions, and research gaps.

3. Global Distribution and Extraction Trends

The global distribution of critical minerals is highly uneven, with a limited number of countries ac-

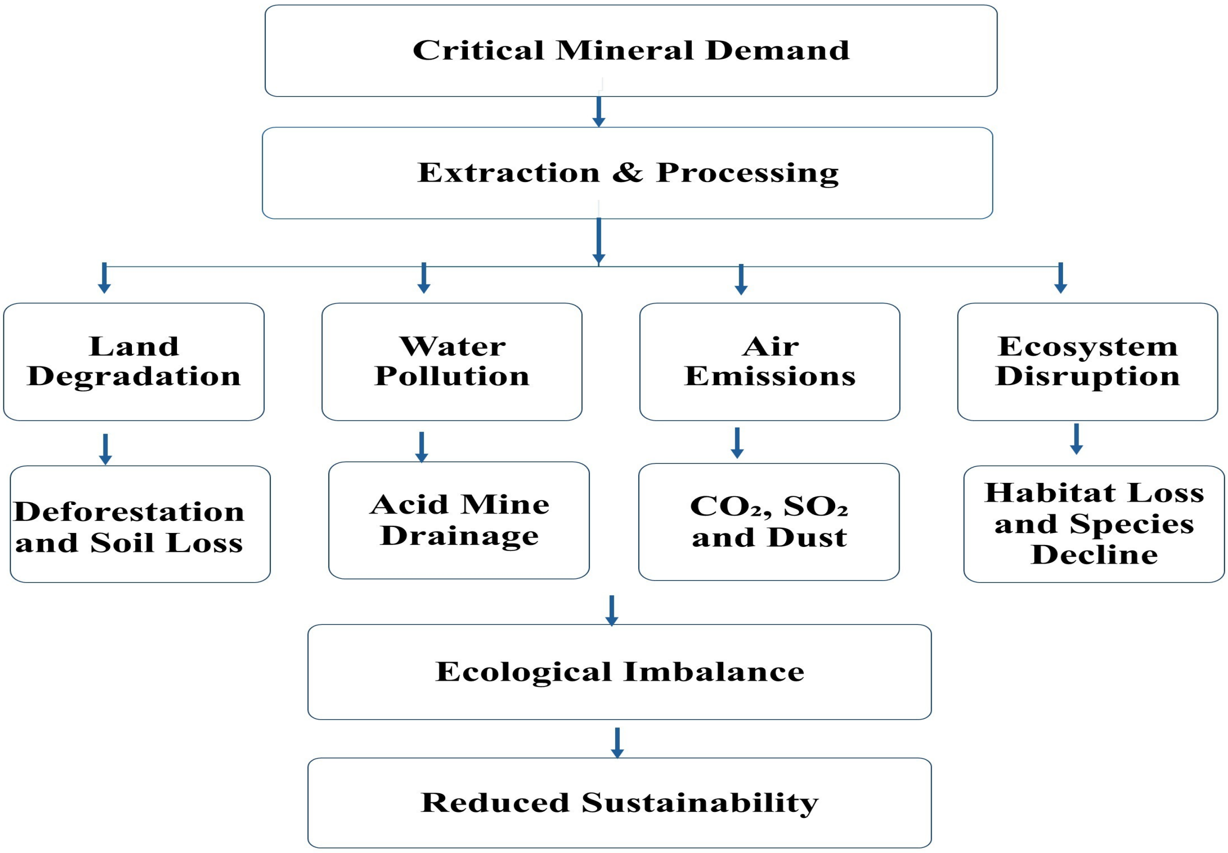

Fig. 1. Integrated framework of critical mineral extraction, environmental impacts, and sustainability pathways.

counting for a substantial share of global reserves and production. According to the Global Critical Minerals Outlook (IEA, 2024a), lithium reserves are concentrated within the "Lithium Triangle" of Chile, Argentina, and Bolivia, alongside significant deposits in Australia. Cobalt production is overwhelmingly centred in the Democratic Republic of Congo (DRC), which supplies nearly 70% of global output, often through artisanal and environmentally challenging practices (Ali et al., 2017; Sovacool et al., 2020). Nickel resources are abundant in Indonesia and the Philippines, together accounting for more than half of global supply, while rare earth elements (REEs) remain dominated by China, which controls over 60% of mining and 85% of refining capacity (Ikeh, 2025; Lederer et al., 2025). Graphite production is similarly concentrated in China, Mozambique, and Madagascar, whereas copper is primarily mined in Chile and Peru, accounting for nearly 40% of global supply (Vera et al., 2023; Sen et al., 2026). This strong geographic concentration creates strategic supply-chain vulnerabilities and localises environmental pressures within a limited number of producing regions. The global spatial distribution of major critical minerals is shown in Fig. 2.

Extraction methods vary across minerals and regions, shaping their environmental footprint. Lithium is obtained through brine evaporation in South America and hard-rock mining in Australia, both of which pose water and land challenges (Vera et al., 2023; IEA, 2024b). Brine-based extraction in arid Chile and Argentina is frequently associated with high evaporative water losses and groundwater stress, whereas Australian hard-rock spodumene mining generally requires more energy-intensive crushing, transport, and thermal conversion processes. Cobalt is largely a by-product of copper mining, with artisanal operations in the DRC raising concerns about deforestation, water contamination, and public health (Banza Lubaba Nkulu et al., 2018). Nickel extraction from laterite and sulfide ores requires energy-intensive smelting, contributing to high greenhouse gas emissions (Msumange et al., 2026). Rare earths are extracted through acid leaching and solvent pro-

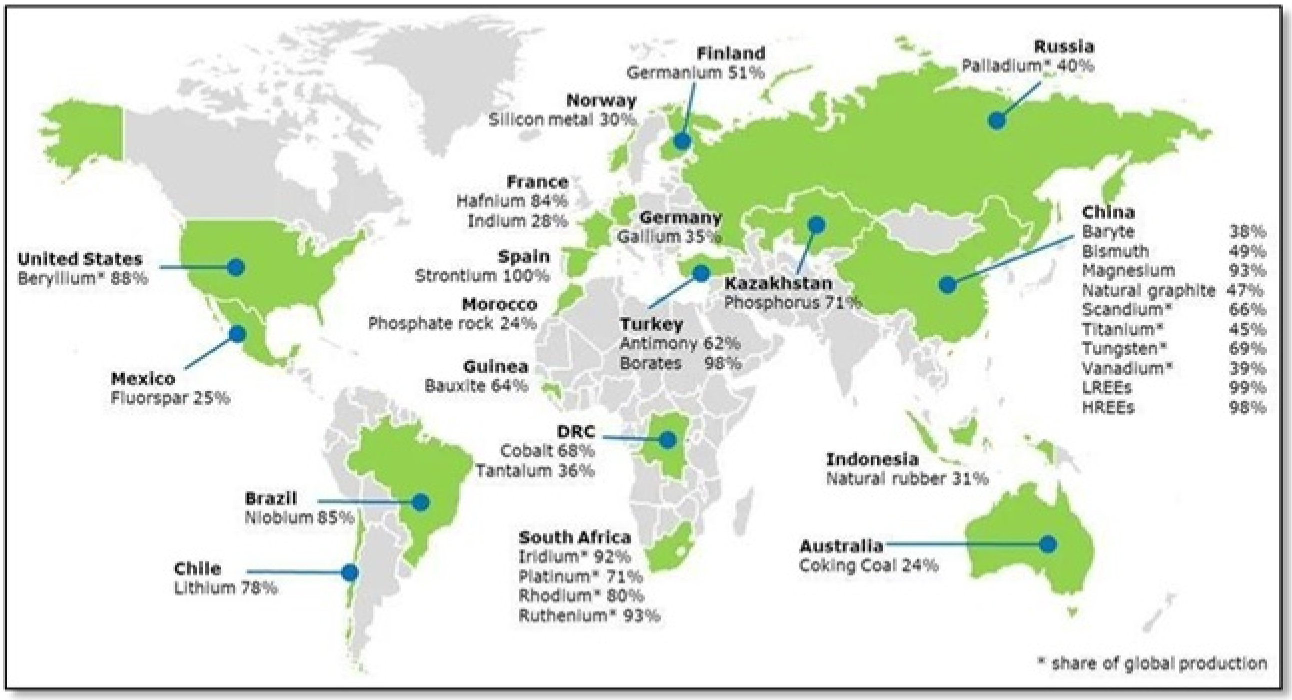

Fig. 2. Global map of critical minerals with specified major supplier countries (Source: European Commission, 2020).

cesses, generating radioactive tailings with long-term ecological risks (Gkika et al., 2024). Graphite mining involves open-pit operations and chemical purification, while copper extraction relies on large-scale open-pit mining and flotation techniques (Vasumathi et al., 2023).

4. Environmental Dynamics and Sustainability Challenges of Critical Mineral Extraction

The rapid expansion of critical mineral extraction has intensified concerns regarding its environmental footprint. Although these resources are indispensable for clean energy technologies, their mining and processing often generate high ecological and social costs. Recent studies emphasise that without robust safeguards and proper governance mechanisms, the pursuit of a low-carbon economy risks may inadvertently compromise broader sustainability objectives (Sovacool et al., 2019). This rapid expansion has pushed mining activities into previously underexploited and ecologically sensitive regions, thereby intensifying environmental pressures at local and regional scales (Siddi, 2023).

The concentration of production in a few geographic regions further amplifies these impacts, as environmental burdens become localised while benefits are distributed globally. Such asymmetry highlights the need to critically assess not only the quantity of extraction but also its spatial implications.

4.1. Landscape Transformation and Ecological Fragmentation

One of the most significant environmental consequences of critical mineral extraction is the large-scale alteration of terrestrial landscapes. Open-pit mining, associated infrastructure development, and waste disposal activities significantly alter natural landforms, leading to deforestation, soil degradation, and habitat fragmentation (Mudd, 2023; Sonter et al., 2020).

The impacts of these transformations extend beyond immediate mining sites, affecting surrounding ecosystems through increasing sedimentation, altered drainage patterns, and loss of ecological connectivity. Recent studies emphasise that such landscape changes reduce ecosystem resilience and impair essential services, including carbon sequestration and nutrient cycling (Kumar, 2024). Furthermore, the cumulative and long-term nature of these impacts suggests that land degradation associated with critical mineral extraction is both spatially extensive and temporally persistent. For example, expansion of nickel and bauxite mining in tropical regions has been associated with accelerated forest loss and biomass decline. In contrast, open-pit copper mining in arid terrains often causes long-term soil disturbance and geomorphic instability.

4.2. Resource Consumption and Regional Variability

Resource consumption associated with critical mineral extraction varies significantly across extraction technologies and regional settings. Lithium extraction from brine systems in Chile's Atacama region consumes substantial groundwater resources through evaporation-based processing, whereas hard-rock mining in Australia primarily consumes water during beneficiation and mineral processing. Such regional variability demonstrates that environmental burdens cannot be generalised across all extraction systems.

4.3. Hydrogeochemical Stress and Water Resource Vulnerability

Water-related impacts are among the most significant environmental consequences of critical mineral extraction, particularly in arid and semi-arid environments. Lithium brine extraction has been widely reported to cause significant groundwater depletion, altering hydrological balances and affecting dependent ecosystems (Moran et al., 2022; Vera et al., 2023; Rentier et al., 2024; Mousavinezhad et al., 2024).

Comparative studies indicate that lithium extraction from salar brines in Chile and Argentina may consume substantially more water through evaporation-based recovery systems. In contrast, hard-rock spodumene mining in Australia generally uses water primarily during ore processing and beneficiation. Reported water-use intensity may vary from approximately 50 to 500 m^3 per tonne depending on deposit type, technology, and climatic conditions.

In addition to water scarcity, mining and mineral processing activities generate acid mine drainage and mobilise heavy metals, contaminating surface and groundwater systems (Anawar, 2013; Fei, 2010). Such hydrogeochemical alterations pose serious risks to aquatic ecosystems, agricultural productivity, and public health, particularly in communities dependent on local water resources. The combined effects of water scarcity and pollution create complex environmental challenges that require integrated water resource management, long-term monitoring, and stronger regulatory oversight.

4.4. Atmospheric Emissions and the Carbon Intensity Paradox

Despite their role in enabling clean energy technologies, the extraction and processing of critical minerals are often associated with significant greenhouse gas emissions and air pollutants. Energy-intensive processes such as smelting and refining contribute to carbon emissions, while dust and sulfur dioxide emissions degrade air quality (Sankar et al., 2024; Arshad et al., 2025).

Emission intensity varies considerably across producing regions. For instance, lithium production from hard-rock sources has been reported to generate higher lifecycle emissions than some brine-based systems due to energy-intensive crushing and thermal conversion stages. Likewise, copper and nickel operations dependent on coal-based electricity may emit substantially more CO_2 than mines powered by cleaner grids or renewable energy sources.

This highlights an inherent paradox in the global energy transition: the materials essential to decarbonization may be produced through carbon-intensive processes. Addressing this paradox requires transitioning to low-carbon mining technologies and increasing the use of renewable energy in mineral processing (Sovacool et al., 2020; Boafo and Arthur-Holmes, 2025).

4.5. Biodiversity Erosion and Ecosystem Instability

Critical mineral extraction often overlaps with biodiversity-rich regions, leading to habitat destruction, species displacement, and ecosystem fragmentation (Kotarska and Young, 2023; Aska et al., 2025). Wetlands, forests, and coastal ecosystems are particularly vulnerable, with long-term consequences for ecological balance.

Recent research highlights that biodiversity loss linked to mining activities can be irreversible, reducing ecosystem resilience and increasing vulnerability to climate change (Sonter et al., 2018; Padhiary and Kumar, 2024; Nakade and Dhadse, 2024). These findings underscore the need to integrate biodiversity conservation into mining planning and regulatory frameworks.

4.6. Socio-Environmental Inequities and Governance Challenges

Environmental impacts of critical mineral extraction are closely intertwined with socio-economic and

Table 1. Major Critical Minerals, Uses, and Environmental Impacts.

Mineral	Key Applications	Major Producing Regions	Key Environmental Impacts	Recent References
Lithium	Batteries (EVs, storage)	Chile, Australia, Argentina	Water depletion, brine contamination	Paz et al. (2025), Vera et al. (2023)
Cobalt	Lithium-ion batteries	DR Congo	Soil & water contamination, health risks	Banza Lubaba Nkulu et al. (2018)
Nickel	Batteries, alloys	Indonesia, Philippines	Air pollution, deforestation	Mervine et al. (2025)
Copper	Electrical systems	Chile, Peru	Land degradation, tailings waste	Fuentes et al. (2021)
Rare Earth Elements	Wind turbines, electronics	China	Toxic waste, chemical pollution	Dutta et al. (2016)

Table 2. Environmental Impacts vs Mitigation Strategies.

Environmental Issue	Key Causes	Impacts	Mitigation Strategies	References
Land degradation	Open-pit mining	Deforestation, habitat loss	Land reclamation, controlled mining	Sonter et al. (2020)
Water scarcity	Brine extraction	Aquifer depletion	Water recycling, efficient extraction	Paz et al. (2025)
Water pollution	Acid mine drainage	Toxic contamination	Wastewater treatment	Ouedraogo and Kilolo (2024)
Air pollution	Smelting, refining	CO_2, SO_2 emissions	Cleaner technologies	Liang et al. (2017)
Biodiversity loss	Habitat destruction	Species decline	Protected zones, impact assessment	Kumar (2024)

Table 3. Circular Economy Potential in Critical Minerals.

Strategy	Description	Benefits	Limitations	References
Recycling	Recover metals from e-waste	Reduces mining demand	Low recovery efficiency	Hossain and Sahajwalla (2024)
Reuse	Extending product life	Resource efficiency	Market limitations	Tutar and Erden (2026)
Substitution	Alternative materials	Reduces dependency	Technological constraints	Acheampong and Abban (2026)
Urban Mining	Extraction from waste	Sustainable sourcing	Cost-intensive	Bahini et al. (2024)

ethical considerations. In many regions, mining activities are associated with hazardous working conditions, human rights concerns, and the displacement of local communities, particularly in artisanal and small-scale mining sectors (Banza Lubaba Nkulu et al., 2018; Abe, 2025). Furthermore, the uneven distribution of economic benefits and environmental burdens raises critical issues of environmental justice, as local communities often bear the costs of resource extraction while global industries derive the benefits (Lèbre et al., 2020; Sovacool et al., 2020). These challenges highlight the importance of transparent governance, inclusive decision-making, and equitable benefit-sharing mechanisms. A summary of major critical minerals, their applications, and associated environmental impacts is presented in Table 1.

5. Sustainable Pathways for Critical Minerals

Addressing the environmental challenges associated with critical mineral extraction requires a holistic, multidimensional framework that goes beyond conventional mitigation strategies. Emerging evidence highlights the importance of circular economy approaches such as recycling, material efficiency, and resource optimisation as effective pathways to reduce dependence on primary extraction and minimise environmental burdens (Shimizu and Owada, 2024; Hossain and Sahajwalla, 2024). Key environmental challenges and corresponding mitigation strategies are summarised in Table 2. The potential of circular economy strategies in critical mineral sustainability is outlined in Table 3.

Complementing these approaches, technological innovations, including bio-leaching and direct lithium extraction, present promising opportunities to lower ecological footprints by improving process efficiency and reducing chemical and water usage (Dutta et al., 2016). At the same time, evolving policy frameworks at national and international levels increasingly emphasise the need for transparent, ethical, and environmentally responsible supply chains, supported by regulatory mechanisms that enforce sustainability standards and accountability (Hund et al., 2020; European Commission, 2023). However, beyond these technical and policy interventions, a broader conceptual shift is necessary. The energy transition must be seen solely as a substitution of fossil fuels with renewable energy systems, rather than as a fundamental transformation in patterns of resource extraction, consumption, and governance. Without such a shift, there is a risk of merely relocating environmental pressures from carbon-intensive energy systems to mineral-dependent technologies. Therefore, integrating principles of resource efficiency, ecological integrity, and social equity into the core of energy transition strategies is essential. This calls for moving beyond a carbon-centric paradigm toward a more inclusive and systems-oriented perspective that recognises the interconnectedness of environmental, technological, and socio-economic dimensions (Sovacool et al., 2020; Owen et al., 2023). The lifecycle stages of critical minerals and their environmental in-

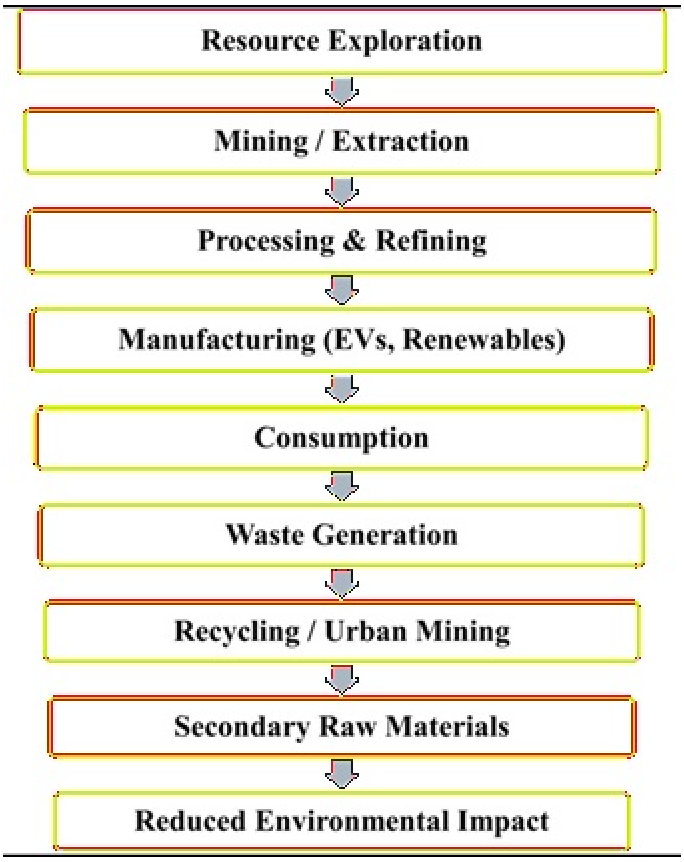

Fig. 3. Schematic representation of critical mineral lifecycle stages showing extraction, processing, utilisation, recycling pathways, and associated environmental interactions.

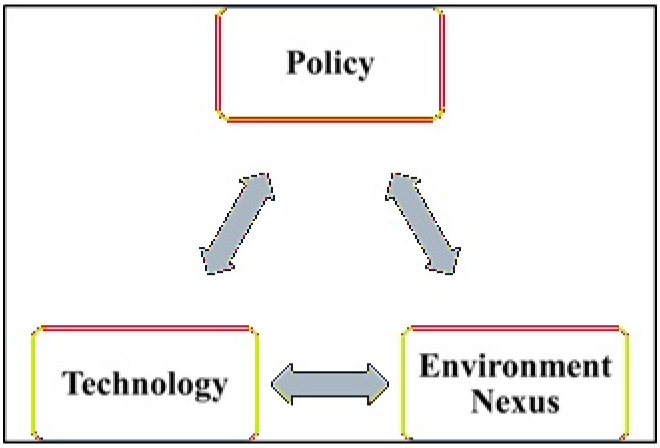

Fig. 4. Policy technology environment nexus for sustainable critical mineral development.

teractions are illustrated in Fig. 3. The integration of policy, technology, and environmental considerations is illustrated in Fig. 4.

6. Conclusion

The accelerating demand for critical minerals underscores their indispensable role in enabling the global transition toward low-carbon energy systems. However, as this review demonstrates, the extraction and processing of these resources are associated with significant environmental and socio-ecological challenges that cannot be overlooked. Land degradation, water scarcity and contamination, atmospheric emissions, and biodiversity loss collectively reveal that critical mineral development carries a substantial ecological footprint. These impacts are often concentrated in environmentally sensitive and socio-

Fig. 5. Conceptual representation of the sustainability paradox illustrating the trade-off between clean energy transition goals and environmental impacts associated with critical mineral extraction.

economically vulnerable regions, raising important concerns regarding sustainability and environmental justice. This paradox is conceptually illustrated in Fig. 5.

Environmental impacts and mitigation strategies are directly interconnected. Water depletion may be partially addressed through water recycling and direct lithium extraction technologies; atmospheric emissions may be reduced through renewable-powered mineral processing; biodiversity impacts may be mitigated through ecological restoration and protected-area planning.

A key insight emerging from this review is the existence of a fundamental sustainability paradox. While critical minerals are essential for decarbonization, their extraction processes may undermine the very environmental goals they are intended to support. Addressing this paradox requires a paradigm shift from a narrow, carbon-centric approach to a more integrated framework that prioritises resource efficiency, ecological integrity, and social equity.

The review further highlights that multiple sustainable pathways do exist. Circular economy strategies, technological innovations in low-impact extraction, and evolving policy frameworks offer promising avenues to reduce environmental burdens. However, their effectiveness depends on large-scale implementation, strong regulatory mechanisms, and global cooperation.

From a policy perspective, governments should prioritise standardised life-cycle assessment (LCA) frameworks, stricter environmental clearance mechanisms, transparent ESG-based disclosure systems, and stronger community benefit-sharing models. Industrial stakeholders should accelerate the adoption of renewable-energy-powered mining operations, electrified haulage systems, cleaner mineral processing technologies, and large-scale recycling infrastructure.

Future research should focus on cumulative environmental impact assessment, long-term ecological monitoring, region-specific comparative studies, AI- and remote-sensing-based environmental surveillance, and socio-economic justice indicators for mining communities (Sahoo, 2024). Such interdisciplinary efforts are essential to bridge current knowledge gaps and support evidence-based decision-making. Ultimately, achieving a truly sustainable energy transition will depend on rethinking how critical minerals are sourced, managed, and utilised. The future of clean energy must therefore be built not only on mineral security but also on environmental responsibility, technological innovation, and equitable global governance.

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