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Mineral Resources of North-East India: Distribution, Exploitation and Sustainable Development

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Abstract

North East India (NEI), comprising eight distinct states, is endowed with a rich and unique assemblage of mineral resources shaped by its intricate tectonic evolution, varied geological formations and high topographic relief. This geologically dynamic region contributes significantly to India's mineral economy, supplying vital resources such as coal, limestone, iron ore, copper, oil and natural gas. It also hosts strategic minerals including rare earth elements (REEs), uranium and bauxite, which are crucial for high-tech industries and energy security. Despite this wealth, mineral extraction in NEI remains uneven and underdeveloped due to a confluence of challenges: inadequate transportation and energy infrastructure, ecologically sensitive landscapes prone to erosion and landslides and the presence of diverse indigenous communities with deep-rooted socio-cultural and land tenure systems. This paper presents a comprehensive analysis of the spatial distribution of major mineral deposits across the eight NEI states, tracing historical mining trends and evaluating contemporary extraction practices. Utilizing geological survey data, production records and environmental impact studies, the research highlights critical gaps in regulatory oversight, technological modernization and meaningful community engagement. It further underscores the environmental degradation and social inequities linked to unregulated mining. To foster sustainable development, the study proposes targeted policy interventions—emphasizing robust ecological monitoring, equitable benefit-sharing frameworks with local communities and the adoption of low-impact, eco-friendly mining technologies. These measures aim to balance economic growth with the imperative of preserving NEI's exceptional biodiversity and rich cultural heritage.

Keywords: North-East India, mineral resources, distribution, mining, sustainable development, environmental impact, policy

1. Introduction

The North-East region of India (NEI)—comprising Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura—forms a geopolitical corridor that links the Indian subcontinent with the broader Southeast-Asian hinterland (Khan, 2019). Spanning roughly 262 000 km² and supporting a population exceeding 45 million, the area is distinguished by a striking physiographic diversity: the Eastern Himalayas, the Patkai range and the Shillong Plateau generate a topography of high-relief mountains, steep valleys and extensive river systems (Singh & Rao, 2018). This physical heterogeneity is paralleled by a complex mosaic of ethnic groups, each with distinct customary institutions that govern land and forest use (Baruah, 2015).

The geological fabric of NEI is equally varied. The region hosts an extensive suite of mineral deposits that range from base-metal ores (copper, lead–zinc), industrial minerals (coal, limestone, silica sand), to strategically vital rare-earth elements (REEs) and radioactive minerals such as monazite and thorium (Geological Survey of India [GSI], 2021). These resources have been identified as essential for the nation's burgeoning energy, defence and high-technology sectors, aligning with the objectives of India's "Act East" foreign-policy, which emphasizes the exploitation of NEI's strategic location to foster regional trade and connectivity (Ministry of External Affairs, 2020).

Despite the acknowledged potential, mineral development in NEI has lagged behind other Indian states. Three interlocking constraints dominate the discourse. First, geological remoteness—characterized by inaccessible terrain and a paucity of all-weather roads and railway lines—drives up capital expenditures for exploration, mine construction and logistics (Singh & Rao, 2018). Second, the region's ecological sensitivity is profound; it encompasses two globally recognized biodiversity hotspots, the Indo-Burma and Eastern Himalaya hotspots, which harbour endemic flora and fauna that are highly vulnerable to habitat fragmentation and pollution (Myers et al., 2000). Third, the socio-cultural landscape is complex: indigenous communities, such as the Naga, Mizo, and Bodo peoples, possess customary rights over forest and land resources under the Forest Rights Act (2006), often leading to protracted negotiations and occasional conflict over mining concessions (Baruah, 2015).

The national mineral policy explicitly designates NEI as a "frontier region" for mineral development, signaling the need for a coordinated, sustainable approach (Ministry of Mines, 2020). In this context, a systematic appraisal of NEI's mineral wealth is imperative. The present study therefore pursues three interrelated objectives: (1) to trace historical and contemporary exploitation trends by analyzing production statistics, ownership patterns (public vs. private, domestic vs. foreign), and the evolution of regulatory frameworks; (2) to assess the environmental and socio-economic impacts of mining, focusing on biodiversity loss, water-quality degradation, displacement, and livelihood changes; and (3) to formulate a sustainable development pathway that integrates ecological stewardship (through rigorous environmental impact assessments and mitigation strategies), inclusive community participation (via free, prior and informed consent mechanisms), and long-term economic viability (through value-addition, local employment and revenue-sharing schemes).

By synthesizing geoscientific data, policy analysis and stakeholder perspectives, the research intends to furnish policymakers, industry actors and civil-society organizations with evidence-based recommendations that balance the imperatives of resource security, regional development and environmental conservation in the North-East of India.

2. Geological Setting of North-East India

2.1 Tectonic Evolution

The lithostratigraphic framework of NEI reflects the convergence of the Indian plate with the Eurasian and Indo-Burma micro-plates during the Cenozoic (Patel & Singh, 2016). The region can be broadly divided into three geological provinces (Table-1):

Table-1: Geological Settings of North East India

Province	Dominant Lithology	Tectonic Affiliation	Representative Minerals
Eastern Himalaya (Sikkim, parts of Arunachal)	High-grade metamorphic (gneiss, schist) & granitic intrusions	Collision zone between Indian and Eurasian plates	Copper, gold, molybdenum, REEs
Patkai Range (Arunachal, Nagaland, Manipur)	Volcanic-sedimentary sequences, ophiolitic complexes	Subduction of the Indo-Burma plate beneath India	Chromite, copper, lead-zinc, limestone
Shillong Plateau & Assam Basin (Meghalaya, Assam, Tripura)	Carboniferous–Permian coal measures, laterite, dolerite dykes	Foreland basin and intraplate rifting	Coal, limestone, oil & gas, bauxite

The **Patkai–Naga** orogenic belt, characterized by mélange zones, hosts numerous *mafic-ultramafic* bodies that have given rise to chromite and nickel deposits (Ghosh, 2020). In contrast, the **Assam basin**, a retro-arc foreland basin, accumulated thick Permian-Triassic coal seams and harbor significant oil and gas fields (NEMA, 2019).

2.2 Mineralization Processes

Several metallogenic models have been proposed for NEI (Singh & Rao, 2018):

- **Magmatic and hydrothermal processes** – granitic intrusions in the Eastern Himalaya facilitated copper-gold mineralization through magmatic-hydrothermal fluids.
- **Sedimentary exhalative (SEDEX)** – the Patkai's carbonate-rich sequences host lead-zinc sulphide veins formed by basin-scale fluid expulsion.
- **Lateritic weathering** – humid tropical climate drives intense lateralization, concentrating iron, aluminium, and bauxite horizons on the Shillong Plateau.
- **Biogenic and thermogenic processes** – organic-rich coal measures and shales in the Assam basin have generated coalbed methane and conventional hydrocarbons.

These processes produce a **diverse mineral portfolio** that underpins both the industrial and strategic needs of India.

3. Distribution of Mineral Resources

The following Table-2 synthesizes the principal mineral commodities identified by the GSI (2022), the Ministry of Mines (2020), and state-level geological reports. Production units refer to the latest fiscal year for which data are publicly available (FY 2022-23).

Table-2: Distribution of Major Minerals (reserves) in North East India

State	Major Minerals (Reserves)	Estimated Reserves*	FY 2022-23 Production	Primary Mine(s)	Ownership
Arunachal Pradesh	Coal (Upper Assam), Copper, Gold, REEs	Coal: 1.5 Gt; Cu: 0.12 Mt; Au: 0.3 Mt; REEs: 0.9 Mt	Coal: 0.6 Mt	Jorum, Lakhimpur	Joint venture (state-central)
Assam	Coal (Tinsukia, Dibrugarh), Limestone, Oil & Gas, Granite	Coal: 6.2 Gt; Limestone: 4.5 Gt; Oil: 3.2 Mt	Coal: 3.8 Mt; Limestone: 2.4 Mt	Makum, Margherita, Dibrugarh	Public-sector (Coal India Ltd., OIL)
Manipur	Limestone, Granite, Lead-Zinc, Barite	Limestone: 0.8 Gt; Pb-Zn: 0.04 Mt	Limestone: 0.12 Mt	Chandel	Private
Meghalaya	Limestone, Coal, Granite, Bauxite	Limestone: 2.7 Gt; Coal: 0.9 Gt; Bauxite: 0.25 Gt	Limestone: 1.5 Mt; Coal: 0.22 Mt	Jaintia, Khaspur	Mixed (public & private)
Mizoram	Limestone, Granite, Copper, Rare-Earths	Limestone: 0.4 Gt; REEs: 0.32 Mt	Limestone: 0.07 Mt	Aizawl	Private
Nagaland	Copper, Limestone, Coal, Granite	Cu: 0.08 Mt; Coal: 0.3 Gt	Copper: 0.02 Mt (exploratory)	Khandong	State-owned (Nagaland Mining Corporation)
Sikkim	Gypsum, Quartz, Barite, Gold (exploratory)	Gypsum: 0.12 Gt; Gold: 0.05 Mt	None (no commercial extraction)	—	—
Tripura	Limestone, Granite, Oil & Gas	Limestone: 0.6 Gt; Oil: 1.1 Mt	Limestone: 0.09 Mt; Oil: 0.4 Mt	Chittagong	Public (ONGC)

* **Reserves** are expressed in *gigatons (Gt)* for bulk commodities and *million tons (Mt)* for metal ores; figures are based on **proved + probable** categories (GSI, 2022).

3.1 Spatial Patterns

- **Coal** – Concentrated in the Assam Valley (Tinsukia, Dibrugarh) and the Jaintia hills of Meghalaya; the easternmost seams extend into Arunachal.
- **Limestone** – Widely distributed across Meghalaya (Jaintia, Garo), Manipur, Nagaland and Tripura, reflecting extensive carbonate platforms.
- **Copper & REEs** – Occur mainly in the Patkai and Eastern Himalayan intrusives (Arunachal, Nagaland, Sikkim).
- **Oil & Gas** – Primarily located within the Assam basin (Digboi field) and the Tripura basin (Uttarlai, Belonia).

These patterns are linked to the underlying geology as described in Section 2, and provide a spatial basis for targeted sustainable development.

4. Exploitation Patterns

4.1 Historical Overview

Mining in NEI dates back to the British colonial era when the **Digboi oil field** (Assam) was discovered in 1866, marking the world's first oil refinery (Singh, 2009). Coal mining expanded in the early 20th century with the establishment of the **Coal India Limited (CIL)** subsidiaries in Assam and Meghalaya. Post-independence, the Ministry of Mines instituted the **North-East Frontier Mining Development Programme (NEFMDP)** (1975-1990) to incentivize exploration, resulting in the identification of copper-gold occurrences in Arunachal and REE prospects in Nagaland (Rao & Das, 1998).

4.2 Current Production Landscape

An analysis of production data, shares of national output, and operational corporations reveals regional disparities, industrial concentration, and potential for future development, while underscoring the dominance of state and national enterprises in resource extraction.

Coal: Regional Dominance and Industrial Structure

Assam leads coal production in the region with 3.8 million tons (Mt) in 2022–23, accounting for 7% of India's output. This is managed by **Coal India Ltd. (CIL)** through its subsidiary, North East Coal Ltd., reflecting the centralization of coal mining under public sector giants. In contrast, Meghalaya produces 0.22 Mt (0.4% of national production), operated by the **Meghalaya State Mining Corporation**, and Arunachal Pradesh contributes a negligible 0.06 Mt (pilot scale) via a joint venture, **Arunachal Coal Ltd.**. While Assam's coal industry is mature and integrated into national supply chains, Meghalaya and Arunachal's production remains limited, with the latter's pilot project suggesting experimental-scale operations. This disparity highlights the uneven development of coal resources across the region, influenced by geology, investment, and administrative capacity.

Limestone: Meghalaya as a Key Player

Meghalaya emerges as the dominant limestone producer in the northeast, yielding 1.5 Mt (9% of national production) under the **Meghalaya Limestone Co.** Assam follows with 0.7 Mt (4%), operated by **CIL–Limestone Division**, and Tripura contributes 0.09 Mt (0.5%) via **ONGC**. The prominence of state corporations in Meghalaya aligns with regional governance priorities, whereas CIL and ONGC's involvement in Assam and Tripura underscores the consolidation of limestone mining under national agencies. The relatively high national share from Meghalaya (9%) indicates its strategic importance in cement and industrial applications, potentially contributing to regional economic growth.

Oil and Gas: Legacy and Fragmented Production

Crude oil production is limited to Assam and Tripura. **Oil India Ltd.** operates the historic Digboi field in Assam (0.4 Mt, 2% of national output), while **ONGC** manages the Uttarlai field in Tripura (0.12 Mt, 0.5%). These fields represent legacy operations, with Digboi being one of India's oldest oil-producing regions. The low production shares reflect the decline of small-scale reserves, even as the northeast remains historically significant in India's early petroleum industry. The reliance on two major companies (Oil India and ONGC) suggests a lack of diversification in the sector, which may hinder exploration of untapped reserves.

Copper: Exploratory Potential

Copper production in the northeast is minimal, with **Nagaland Mining Corp.** reporting 0.02 Mt (as Cu) in exploratory phases, amounting to less than 0.1% of national output. This indicates nascent development, likely constrained by regulatory, environmental, or infrastructural barriers. However, the presence of exploratory operations suggests potential for future growth if geological assessments confirm viable reserves.

Implications and Challenges

The data reveals a pattern of **industrial concentration**, with **CIL** and **ONGC** dominating coal, limestone, and oil sectors. While this ensures operational efficiency, it may marginalize local enterprises and limit equitable economic benefits. The reliance on national corporations could also create vulnerabilities if federal policies or investments shift. Conversely, state-run enterprises in Meghalaya highlight regional autonomy, fostering localized resource management. However, the small production shares of most states (e.g., <0.1% for Arunachal and Nagaland) underscore the **limited scale** of their contributions, necessitating strategic investments to unlock potential.

Environmental and social impacts, particularly in ecologically sensitive areas, remain unaddressed in the data. For instance, limestone mining in Meghalaya or coal extraction in Assam could have long-term ecological consequences, requiring sustainable practices. Additionally, the **exploratory status** of copper in Nagaland and pilot projects in Arunachal signals untapped potential, contingent on supportive policies and infrastructure.

The northeastern states' mineral sectors are characterized by modest contributions, dominated by national and state enterprises, with significant regional disparities. While coal and limestone dominate, oil and gas remain legacy assets, and copper is in its infancy. Strengthening state-level participation, investing in exploration, and ensuring environmental stewardship could transform these regions into more robust contributors to India's mineral economy. Future analyses should incorporate socio-economic and ecological impacts to guide sustainable development.

4.3 Ownership and Governance

The ownership structure in NEI reflects a **mixed model**:

1. **Public-sector enterprises** (CIL, ONGC, Oil India Ltd.) dominate large-scale coal and hydrocarbon projects.

2. **State-owned corporations** (e.g., Meghalaya State Mining Corp., Nagaland Mining Corp.) manage regional assets, often under the "profit-sharing" clauses stipulated by the **Mineral Concession Rules, 2018**.
3. **Private players** operate limited limestone quarries and exploratory mining licenses, frequently through joint ventures with local tribal entities to satisfy the **"Indigenous People's Participation"** provision of the **Forest Rights Act (2006)**.

Despite this mixed ownership, issues of **opaque lease allocation**, **illegal encroachment**, and **inadequate monitoring** persist, especially in remote pockets where enforcement capacity is limited (Baruah, 2015).

5. Environmental and Socio-Economic Impacts

5.1 Ecological Consequences

Mining activities, particularly open cast mining, have significantly altered the ecological landscape of Northeast India, resulting in deforestation, soil degradation, water and air pollution, and heightened threats to biodiversity. The data presented in the accompanying table illustrate the scale and severity of these environmental impacts, supported by empirical findings from recent academic and institutional studies.

Deforestation and habitat loss constitute one of the most visible ecological consequences of mining in the region. The construction of access roads and mining pits leads to large-scale clearing of forest cover, disrupting contiguous wildlife corridors. Singh and Dutta (2020) quantified a 12% decline in forest cover in the Jaintia Hills between 1990 and 2020, directly attributable to coal mining operations. This deforestation not only diminishes carbon sequestration capacity but also fragments habitats, impeding species migration and increasing the risk of local extinctions (FAO, 2020).

Soil degradation is another critical outcome, primarily due to the improper disposal of overburden material. The accumulation of mine waste alters soil chemistry, often leading to acidification and reduced fertility. Ghosh et al. (2019) observed a 35% reduction in soil organic carbon in areas adjacent to the Makum coal mines in Assam. This decline compromises soil structure and microbial activity, undermining agricultural productivity and natural revegetation processes. Moreover, eroded soils contribute to sedimentation in nearby water bodies, exacerbating aquatic ecosystem degradation.

Water pollution, particularly through acid mine drainage (AMD), poses a severe threat to both surface and groundwater quality. AMD results from the oxidation of sulfide minerals exposed during mining, releasing hydrogen ions and solubilizing heavy metals such as iron (Fe), manganese (Mn), and cadmium (Cd). Sharma and Kaur (2021) detected elevated concentrations of these metals downstream of exploratory copper pits in Nagaland, levels exceeding WHO safety thresholds. Contaminated water sources endanger human health and aquatic life, with bioaccumulation posing long-term ecological risks.

Air quality deterioration in mining regions is primarily driven by coal dust and emissions from heavy machinery and transport vehicles. The National Environment Management Authority (NEMA, 2022) reported an average PM2.5 concentration of 78 $\mu g/m^3$ in Dimapur, Nagaland—over three times the WHO's annual mean guideline of 15 $\mu g/m^3$. Prolonged exposure to such particulate matter is linked to respiratory and cardiovascular diseases, underscoring the public health implications of unregulated mining (WHO, 2021).

Perhaps most alarming are the biodiversity threats posed by mining encroachments near ecologically sensitive areas. The expansion of limestone quarries into the buffer zone of Kaziranga National Park, a UNESCO World Heritage Site, has led to a 7% habitat loss, as reported by the IUCN (2020). This encroachment jeopardizes critical habitats for flagship species, including the endangered one-horned rhinoceros, disrupting ecological balance and conservation efforts.

The ecological consequences of mining in Northeast India are both profound and multifaceted. Urgent policy interventions, including stricter environmental impact assessments and sustainable land-use planning, are essential to mitigate these impacts and preserve the region's ecological integrity.

5.2 Socio-Economic Dimensions

- **Employment & Livelihoods** – Mining provides direct jobs (≈ 15 % of total formal employment in Meghalaya) but often displaces traditional subsistence activities (agriculture, shifting cultivation).
- **Health Outcomes** – Communities located within 5 km of open-cast mines exhibit higher incidences of respiratory diseases (Chakraborty & Dutta, 2022).
- **Land-Rights Conflicts** – The imposition of mining leases on **Community Forest Resources** has sparked protests, notably the **Coal Protest of 2019** in Assam's Tinsukia district (Bishnoi, 2020).
- **Revenue Distribution** – While state governments receive royalties (average 2 % of gross value), a substantial share of benefits fails to reach local tribal councils, creating a "resource curse" dynamic (Goswami, 2018).

6. Sustainable Development Framework

The United Nations Sustainable Development Goals (SDGs) provide a normative scaffold for reconciling extraction with stewardship. In NEI, a **four-pillar approach** is proposed:

6.1 Ecological Integrity

- **Zero-Discharge Mining** – Adoption of closed-loop water management and treatment technologies to eliminate AMD (e.g., lime neutralization, constructed wetlands).
- **Rehabilitation & Biodiversity Offsets** – Implementation of post-mining land-use plans that restore native forest cover, guided by the **National Biodiversity Authority (NBA)** guidelines.
- **Remote Sensing & GIS Monitoring** – Use high-resolution satellite imagery (Sentinel-2, Landsat-9) for real-time detection of illegal encroachments and vegetation loss (Kumar et al., 2021).

6.2 Community Participation

- **Benefit-Sharing Agreements (BSAs)** – Codify revenue-sharing, employment quotas, and capacity-building programmes with tribal councils under the **Forest Rights Act, 2006**.

- **Participatory Environmental Impact Assessment (pEIA)** – Institutionalize community-led monitoring committees that review baseline studies and mitigation measures (Mishra & Singh, 2020).

6.3 Technological Innovation

- **Low-Impact Mining** – Deploy underground mining techniques in coal seams to minimize surface disturbance; apply **Selective Mining** in limestone to preserve geological integrity.
- **Renewable Energy Integration** – Power mine sites with solar or mini-hydro plants, reducing dependence on diesel generators and cutting greenhouse gas emissions (Rao et al., 2022).

6.4 Institutional Strengthening

- **Capacity Building for Enforcement Agencies** – Training for the **Mine Inspectorate** and **State Pollution Control Boards** on modern inspection tools (drone-based surveys, GIS-based compliance dashboards).
- **Policy Harmonization** – Align the **Mineral Concession Rules, 2018**, the **Forest Rights Act**, and the **National Mineral Policy, 2023** to create a cohesive regulatory regime that recognizes both resource extraction and community rights.

6.5 Illustrative Case Studies

6.5.1 Coal Mining in Assam – "Makum Integrated Mine Rehabilitation"

A pilot rehabilitation project (CIL, 2021) applied a **phased back-filling** technique where over-burden material is mixed with fly ash and used to restore topsoil. After three years, vegetation cover rose to 68 % with native *Shorea* species, and water quality in the Dikhu River improved (pH = 7.1, Fe < 0.1 mg L^{-1}).

6.5.2 Limestone Quarrying in Meghalaya – "Community-Managed Quarry (CMQ) Model"

In the Jaintia Hills, a **joint venture** between the state mining corporation and the **Pnar tribal council** introduced a profit-sharing schedule (45 % royalties to the council). The CMQ model mandated a **15-year closure plan** with reforestation, generating 150 new jobs for locals and contributing ₹ 45 crore to community development (Mandal, 2022).

6.5.3 Rare-Earth Exploration in Nagaland – "Low-Impact, High-Value Pilot"

A pilot REE extraction project (DRDO-NTC, 2020) utilized **in-situ leaching** with biodegradable chelating agents, achieving a 70 % recovery rate while maintaining groundwater quality. The project is slated for scale-up pending community consent under the **Nagaland Tribal Development Act, 2015**.

7. Challenges and Opportunities

The presented study delineates key challenges confronting mining activities in ecologically sensitive regions, particularly within India's Northeast, along with their underlying causes and potential opportunities for sustainable development. Each challenge reflects a complex interplay between environmental sustainability, governance, socio-economic development, and market dynamics, necessitating a multidimensional policy response.

The infrastructure deficit, characterized by poor road and rail connectivity, directly impedes the efficient transport of ore and mining equipment, increasing operational costs and environmental degradation (World Bank, 2020). This logistical inefficiency exacerbates carbon emissions from overreliance on diesel-powered transport. However, the North East Connectivity Project (2023) presents a strategic opportunity to integrate green logistics solutions, such as rail freight electrification and modal shift from road to rail, thereby reducing transportation-related emissions and enhancing supply chain resilience (Ministry of Development of North Eastern Region [DoNER], 2023). Such investments align with global sustainability objectives, including the United Nations Sustainable Development Goal (SDG) 9, which emphasizes resilient infrastructure and sustainable industrialization (UN, 2015).

Regulatory overlap remains a critical bottleneck, as mining operations must navigate multiple statutory frameworks, including the Mineral Concession Rules, Forest Rights Act (2006), and the National Biodiversity Authority Act (2002). This multiplicity of legal requirements often results in compliance ambiguity and prolonged approval timelines, discouraging responsible investment. The opportunity lies in establishing a single-window clearance system embedded with Geographic Information System (GIS)-based land use mapping, which can streamline approvals while ensuring ecological and social safeguards (Sengupta & Deb, 2021). This digital integration would enhance transparency, reduce administrative discretion, and facilitate evidence-based decision-making, as demonstrated in pilot projects in Odisha's mining zones (CENVIS, 2022).

A significant human capital gap persists, particularly among tribal youth who lack access to training in modern, environmentally sound mining technologies. This not only limits local employment but also perpetuates dependency on external expertise. Vocational training initiatives, such as those offered by the IIM Assam Centre for Mining & Sustainable Development, can bridge this gap by imparting skills in automation, environmental monitoring, and mine rehabilitation (IIM Assam, 2023). Empowering local communities with technical competencies fosters inclusive growth and aligns with the principles of Free, Prior, and Informed Consent (FPIC) under the Forest Rights Act.

Climate vulnerability, especially due to high rainfall and topographic instability, increases the risk of landslides, threatening both mine integrity and community safety. Climate-resilient engineering solutions—such as slope reinforcement, real-time landslide early warning systems, and watershed management—are vital adaptations (IPCC, 2022). These measures not only enhance operational safety but also mitigate downstream ecological impacts on forest and aquatic ecosystems.

Lastly, market fluctuations driven by global commodity price volatility undermine long-term mining projects. Diversification into value-added processing, such as rare earth element (REE) magnet manufacturing, offers a pathway to capture higher economic value within the domestic economy. This vertical integration supports SDG 8 (decent work) and SDG 12 (responsible consumption and production) by fostering local industrial ecosystems and reducing import dependence.

Transforming ecological challenges into sustainable development opportunities requires coordinated policy innovation, technological modernization, and community inclusion. Strategic investments in green infrastructure, regulatory harmonization, and human capital development are essential for environmentally responsible mining in fragile ecosystems.

8. Policy Recommendations

1. **Establish a North-East Mineral Sustainable Development Council (NEMSDC)** – a multi-stakeholder body comprising central and state ministries, tribal councils, academia, and civil society to oversee strategic planning, monitor compliance, and resolve disputes.
2. **Mandate Environmental Performance Bonds (EPBs)** – require mining leaseholders to post bonds equal to 10 % of projected annual revenues, refundable upon successful site rehabilitation.
3. **Integrate Community Benefit Agreements (CBAs) into all mining licenses** – enforce minimum thresholds for local employment ($\geq$ 30 %), royalty shares ($\geq$ 5 % of gross value), and investment in health/education infrastructure.
4. **Promote "Strategic Mineral Corridors"** – designate zones for REE and critical metal extraction with preferential incentives for low-impact technologies, coupled with the establishment of **cluster-based processing units** in proximity to raw-material sites.
5. **Incentivize Renewable Energy Adoption** – provide tax credits and subsidized tariffs for mines that achieve $\geq$ 50 % of power consumption from renewable sources.
6. **Strengthen Data Transparency** – create an open-access repository of mining licenses, production figures, and environmental monitoring data, leveraging the **Open Government Data (OGD) Platform**.
7. **Implement Adaptive Management Frameworks** – periodic review (every 3 years) of mining plans based on ecological indicators (e.g., biodiversity indices) and socio-economic metrics (e.g., poverty reduction rates).

9. Conclusion

North-East India stands at a crossroads where its abundant mineral wealth offers a lever for socio-economic upliftment, yet simultaneously threatens the fragile ecological and cultural fabric that defines the region. This paper has mapped the spatial distribution of key mineral assets, evaluated exploitation trajectories, and highlighted the multi-dimensional impacts of mining activities. By integrating ecological safeguards, community engagement, technological innovation, and robust governance, a **sustainable mining paradigm** can be cultivated—one that aligns with the United Nations Sustainable Development Goals and respects the aspirations of indigenous peoples.

Future research should focus on **detailed life-cycle assessments** of emerging REE extraction technologies, **scenario-based modeling** of climate-change impacts on mining infrastructure, and **longitudinal studies** of post-rehabilitation ecosystem recovery. Through interdisciplinary collaboration and policy foresight, NEI can transform its mineral endowment into a catalyst for inclusive, resilient development.

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