International Journal of Advanced Research in Science, Engineering and Technology

ISSN: 2350-0328

IJARSET IMPACT FACTOR 7.150

Vol. 12, Special Issue, December 2025

National Conference on Earth, Elements and Energy: Interdisciplinary Perspectives (NC3EIP–2025)

Integrated Remote Sensing and GIS Approaches for Critical Mineral Exploration in india

Dr. Trupti Bhattacharjee, Indranil Bhattacharjee

Sapphire Geoconsultants , Mining Associates Pvt Ltd

ABSTRACT: Critical minerals are indispensable to the global energy transition, advanced manufacturing, and defense technologies. India, with its growing industrial and clean-energy demand, has prioritised exploration and secure supply of these resources through the National Critical Mineral Mission (NCMM). This review paper highlights India's geological endowment, outlines major deposits and mining regions, compares global and Indian production trends, and emphasises the role of remote sensing (RS) techniques, and geographic information systems (GIS) in identifying and mapping potential resources. A concise RS–GIS workflow and clean figures demonstrate how digital data integration supports rapid, cost-effective mineral targeting. The review consolidates technical, policy, and scientific perspectives into a single compact reference for researchers and exploration professionals

KEY WORDS: Critical minerals, GIS, remote sensing, hyperspectral, mineral exploration, India, NCMM.

I. RELATED WORK

Remote sensing and geospatial technologies have long been recognised as effective tools for regional-scale mineral exploration due to their synoptic coverage, repeatability, and cost efficiency. Early foundations of remote sensing–based geological mapping demonstrated the utility of multispectral satellite data for lithological discrimination, structural interpretation, and alteration mapping (Gupta, 2017; Jensen, 2022). These approaches enabled identification of surface expressions of mineralisation, particularly in arid and semi-arid terrains.

With the advent of imaging spectroscopy, hyperspectral remote sensing has significantly advanced mineral exploration by allowing direct detection of diagnostic absorption features of alteration minerals. Studies by Hewson et al. (2020) and Aitchison and Buckley (2021) highlighted the effectiveness of hyperspectral datasets in mapping clay minerals, iron oxides, carbonates, and other hydrothermal alteration assemblages closely associated with ore systems. Spaceborne and airborne hyperspectral missions such as AVIRIS-NG, PRISMA, and EnMAP have further expanded the scope of regional mineralogical mapping and end-member spectral analysis.

Integration of remote sensing outputs within GIS environments has enabled systematic mineral perspectivity mapping through multi-criteria decision-making frameworks. Carranza (2018) demonstrated how geological, geochemical, geophysical, and remote sensing layers can be combined using weighted overlay, fuzzy logic, and analytical hierarchy process (AHP) techniques to identify favourable mineral zones. Recent studies increasingly employ machine-learning algorithms such as support vector machines, random forests, and neural networks to enhance predictive accuracy and reduce subjectivity in perspectivity modelling (Mishra & Singh, 2023; Pandey & Sharma, 2024).

Several studies have focused on the fusion of multispectral, hyperspectral, thermal, and radar datasets to improve mineral targeting. Integration of optical and SAR data has proven particularly effective for structural and lineament mapping, which is critical for structurally controlled mineral deposits (Singh & Chatterjee, 2021). Thermal infrared data have also been used to delineate silicate and silica-rich alteration zones, complementing visible–SWIR analyses (Rajendran & Nasir, 2019).

In the Indian context, remote sensing–based mineral exploration studies have primarily concentrated on specific terrains and commodities. Mahesh and Raju (2022) demonstrated the application of ASTER and Sentinel-2 data for alteration mapping in Indian shield regions, while Bhattacharya and Misra (2023) reviewed geospatial integration approaches across selected Indian case studies. Investigations by the Geological Survey of India and Indian Bureau of Mines have provided national-level assessments of critical mineral occurrences and exploration status, but comprehensive integration of advanced RS–GIS workflows with national policy initiatives remains limited (GSI, 2023; IBM, 2024).

Recent policy-oriented studies and global assessments have underscored the strategic importance of critical minerals for clean energy transitions and technological security (World Bank, 2020; IEA, 2023; Pettke & Markl, 2020). Indian-focused analyses highlight the country's growing import dependency and the need for accelerated exploration of lithium, cobalt, nickel, rare earth elements, and other critical commodities (Balaram, 2019; Balaram & Sawant, 2022). However, most existing studies treat geological exploration, geospatial methods, and policy frameworks in isolation.

Overall, the existing literature demonstrates the technical maturity of remote sensing and GIS-based mineral exploration methods but reveals a gap in integrated reviews that link advanced geospatial workflows with India's critical-mineral strategy and national missions such as the National Critical Mineral Mission. Addressing this gap is essential for translating technological advances into coordinated, policy-relevant exploration outcomes.

II. INTRODUCTION

Critical minerals form the foundation of modern clean-energy systems, advanced manufacturing, digital technologies, and national defence infrastructure. They underpin technologies such as lithium-ion batteries, electric mobility, permanent magnets, solar photovoltaics, wind turbines, semiconductors, and high-performance alloys. Minerals including lithium, cobalt, nickel, rare earth elements (REEs), graphite, gallium, and germanium are indispensable to these applications. However, global supply chains for many critical minerals are highly concentrated in a few countries, creating strategic vulnerabilities, price volatility, and significant geopolitical and economic risks.

Recognising these challenges, India has identified critical minerals as a strategic priority and initiated targeted measures to strengthen domestic exploration, processing, recycling, and supply security. The Government of India has notified a list of 30 critical minerals—namely antimony, beryllium, bismuth, cadmium, cobalt, copper, gallium, germanium, graphite, hafnium, indium, lithium, molybdenum, niobium, nickel, platinum group elements (PGE), phosphorus, potash, rare earth elements, rhenium, selenium, silicon, strontium, tantalum, tellurium, tin, titanium, tungsten, vanadium, and zirconium. These minerals originate from diverse primary ores and by-product streams and support a wide range of industrial and technological applications.

Elements such as lithium, cobalt, nickel, graphite, gallium, indium, germanium, tellurium, and REEs are central to batteries, electronics, renewable energy systems, and electric vehicles. Metals including molybdenum, tungsten, niobium, titanium, vanadium, hafnium, and rhenium enhance the performance of advanced alloys used in aerospace, nuclear, and defence sectors. Copper, silicon, phosphorus, potash, and zirconium are critical for infrastructure, agriculture, and energy technologies, while antimony, bismuth, tin, strontium, and selenium play specialised roles in flame retardants, pharmaceuticals, glassmaking, solders, and pyrotechnics. Several critical minerals—particularly gallium, indium, germanium, cadmium, selenium, and tellurium—are predominantly recovered as by-products, further exacerbating supply risks and reinforcing the need for systematic exploration and resource management.

To address these challenges, India has launched the **National Critical Mineral Mission (NCMM)** as a coordinated national framework to enhance supply-chain resilience and self-reliance (Table 1). The mission integrates domestic exploration and mining, acquisition of overseas mineral assets, recycling and circular-economy approaches, trade and market interventions, scientific research and technological development, human resource capacity building, and supportive fiscal and financing mechanisms. Key initiatives under the NCMM include expanded exploration programmes by the Geological Survey of India, overseas asset acquisition through Khanij Bidesh India Ltd. (KABIL), and revised royalty and policy structures to incentivise private sector participation.

Table 1.
National Critical Mineral Mission Components

Sl	Components
1	Increasing Domestic Critical Minerals Production
2	Acquisition of Critical Mineral Assets Abroad
3	Recycling of Critical Minerals
4	Trade and Markets
5	Scientific Research & Technological Advancement for Critical Minerals
6	Human Resource Development
7	Developing Effective Funding, Financing and Fiscal Incentives

Despite India's diverse geological endowment, large areas of prospective terrain remain under-explored, highlighting the need for efficient, scalable, and cost-effective exploration strategies. In this context, remote sensing (RS) and geographic information systems (GIS) provide a powerful framework for accelerating mineral exploration through synoptic terrain analysis, rapid data integration, and predictive prospectivity modelling. The combined use of multispectral, hyperspectral, thermal, and radar datasets enables the detection of lithological units, structural controls, and hydrothermal alteration signatures associated with mineralisation. When integrated within GIS-based workflows and supported by geophysical, geochemical, and field validation data, these techniques significantly reduce exploration risk and improve targeting efficiency.

This paper presents a comprehensive review of India's critical mineral landscape and examines the role of integrated RS–GIS approaches in supporting exploration and resource assessment. The objectives are to (i) outline India's critical mineral endowment and strategic context, (ii) summarise relevant geospatial techniques and RS–GIS workflows for critical-mineral exploration, and (iii) demonstrate how these approaches can be aligned with national initiatives such as the NCMM to enable systematic, sustainable, and policy-relevant exploration outcomes.

III. GLOBAL INDIAN IMPORTANCE

Globally, critical minerals occur in pegmatitic systems (Li, Ta, Be), ultramafic–mafic intrusions (Ni, Co, PGEs), sedimentary evaporites (Li, potash), and metamorphic belts (graphite). India's geological diversity provides comparable settings yet remains under-explored.
India contributes < 2 % of global lithium and cobalt output and about 6–7 % of global graphite production, while Australia, China, and the DRC dominate the supply chain. The gap underscores India's need for accelerated exploration and processing capacity.

IV. GEOLOGICAL SETTINGS AND SPATIAL DISTRIBUTIONOF DEPOSITS AND MINES IN INDIA

India hosts a wide range of geological domains that hold significant potential for the discovery and extraction of critical minerals essential for modern technologies and the green energy transition. Along the coastal tracts of **Kerala, Tamil Nadu, Andhra Pradesh, and Odisha**, extensive **heavy-mineral sand deposits** contain valuable minerals such as ilmenite, rutile, zircon, and monazite, which are important sources of titanium and rare earth elements (REEs). The **pegmatite belts** of **Bihar, Jharkhand, Rajasthan, and Karnataka** are rich in lithium, beryllium, and tantalum-bearing minerals, offering promising prospects for battery and electronic industries. The **graphite-bearing belts** in **Jharkhand, Odisha, and Chhattisgarh** represent key sources for high-grade graphite, a critical material for energy storage and electric vehicles. Similarly, **ultramafic–mafic complexes** such as those in **Sukinda (Odisha)** and **Nuggihalli (Karnataka)** host strategic resources like chromite, nickel, and platinum-group elements. In addition, **REE-bearing carbonatite and alkaline complexes** including **Amba Dongar (Gujarat)**, **Sarnu–Dandali (Rajasthan)**, and **Sung Valley (Meghalaya)** are of great importance for rare earth exploration. Collectively, these diverse geological settings make India a potential global hub for critical mineral resources, supporting its industrial growth, strategic autonomy, and clean energy ambitions.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 12, Special Issue, December 2025
National Conference on Earth, Elements and Energy: Interdisciplinary Perspectives (NC3EIP–2025)
IJARSET IMPACT FACTOR 7.150

V. REMOTE SENSING & GEOSPATIAL TECHNIQUES FOR CRITICAL MINERAL EXPLORATION

1. Conceptual framework

Remote sensing offers a non-invasive, synoptic, repeatable way to detect litho-structural units, hydrothermal alteration zones and surface expressions of mineralisation. When integrated with field geology, geophysics and geochemistry, remote sensing becomes a powerful component of a geospatial mineral-prospectivity workflow.
The workflow (Figure 1 and 2) broadly includes:

- Pre-processing of satellite/airborne imagery
- Extraction of relevant spectral indices
- Use of hyperspectral/hyper-temporal data for mineralogical discrimination (e.g., kaolinite, illite, chlorite, epidote)
- Structural mapping via radar/SAR (lineaments, faults, shear zones)
- Data fusion (optical + thermal + SAR) and machine-learning classification
- GIS-based prospectivity modelling: combining mapped features (alteration, lithology, structure, geophysics, geochemistry) into a multi-criteria decision-making (MCDM) or fuzzy-logic model
- Field-validation: ground truthing, sampling, geochemical assays, and in-situ spectroscopy

2. Remote-sensing sensors & data types

Key sensors and data sources (Table 2) relevant for critical-mineral exploration include:

- Multispectral satellites (e.g., ASTER, Sentinel-2) for alteration mapping;
- Hyperspectral sensors (e.g., PRISMA, AVIRIS-NG) for fine mineral discrimination;
- Radar/SAR (e.g., Sentinel-1, TerraSAR) for structural mapping, lithologic contrasts, and penetrating cloud cover;
- Thermal sensors for mapping thermal anomalies tied to alteration zones;
- UAV/Drone-borne hyperspectral and LiDAR for high-resolution targeting.

Recent research emphasises fusion of optical, thermal and SAR modalities to reduce ambiguity and improve discrimination of mineralised zones. For example: “data fusion between optical, thermal and SAR datasets, supported by field spectroscopy and geochemical validation, enhances spatial accuracy and reduces interpretational ambiguity.”

Table 2.
Sensor Types, their Bands and Applications

Sensor Type	Resolution / Bands	Application
AVIRIS	Airborne hyperspectral - 5–20 m / 224 bands	Detailed alteration mapping
PRISMA	Spaceborne hyperspectral - 30 m / 240 bands	Regional spectral mapping
EnMAP	Hyperspectral satellite 30 m / 242 bands	SWIR alteration detection
ASTER	Multispectral 15–90 m	Iron-oxide, clay, vegetation indices
Sentinel-2	Multispectral 10–20 m	Broad lithological mapping
Landsat-8/9	Multispectral 30 m	Structural and lineament mapping
Sentinel-1 (SAR)	Radar 10 m	

International Journal of Advanced Research in Science, Engineering and Technology

ISSN: 2350-0328

Vol. 12, Special Issue, December 2025

National Conference on Earth, Elements and Energy: Interdisciplinary Perspectives (NC3EIP–2025)

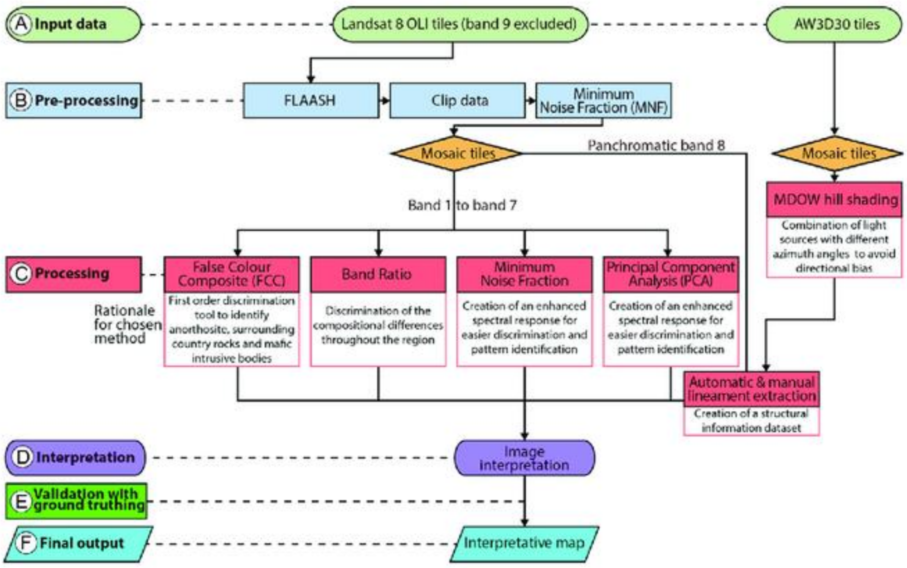

Figure 1. Workflow Diagram in Remote Sensing Data Image Processing (Lehmann Jeremie et al - 2023).

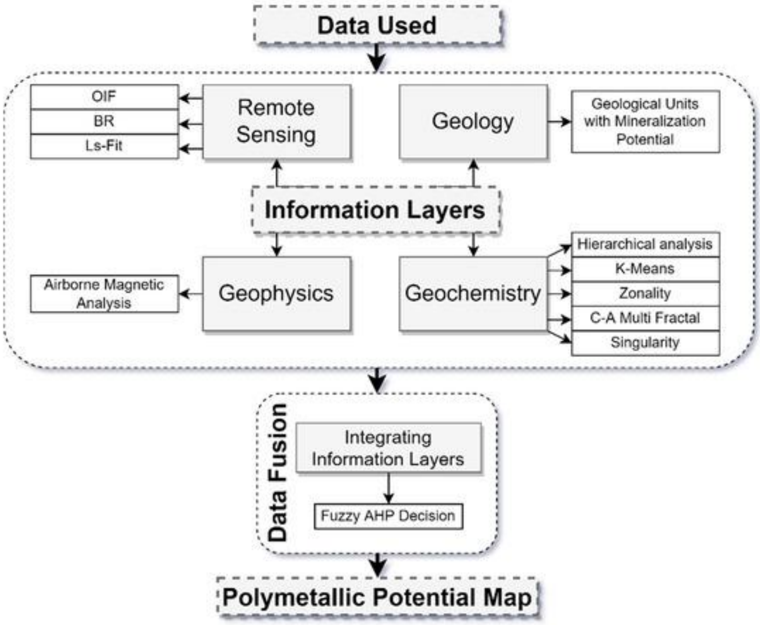

Figure 2. Flow diagram of RS–GIS integration for critical-mineral mapping (Ali Shabani et al - 2022).

STEPS:

1. Data acquisition: Collect geological maps, satellite images (PRISMA, Sentinel-2, ASTER), DEMs, geophysical and geochemical layers.
2. Pre-processing: Perform atmospheric correction, image registration, mosaicking, and filtering.
3. Spectral enhancement: Apply band ratios, principal-component analysis, and mineral indices (iron-oxide, hydroxyl, clay).
4. Classification: Use spectral-angle mapping (SAM), spectral-feature fitting (SFF), or machine-learning classifiers (SVM, RF).
5. Structural analysis: Derive lineaments and faults from DEMs and SAR data.
6. Integration in GIS: Conduct weighted-overlay or fuzzy-logic modelling for mineral prospectivity.
7. Field validation: Sample key sites, collect spectral data, and refine models.
8. Drill targeting: Finalise 3D modelling and prioritise drill sites.

Alteration-mapping and spectral techniques

Identifying alteration minerals (kaolinite, illite, chlorite, epidote, hematite/goethite, carbonate) is key because hydrothermal systems tend to generate such assemblages around ore deposits. Typical remote scanning techniques include:

- Band-ratio indices (e.g., ASTER band 5/band 7 for AlOH clays)
- Principal Component Analysis (PCA) to extract alteration signatures
- Spectral Angle Mapping (SAM) on hyperspectral data to classify minerals
- End-member spectral unmixing to identify minor phases
- Thermal infrared emissivity mapping for silicate alteration and silica-rich zones

Structural/lineament mapping & lithologic discrimination

Critical-mineral deposits are often structurally controlled (faults, shears, lithologic contacts). Remote sensing helps map:

- Lineaments, via directional filtering of optical/SAR imagery
- Shear zones via topographic indices (DEM derived)
- Lithological units via spectral classification (rock type discrimination)

Integration of structural and lithologic data with alteration mapping improves target accuracy.

V. CONCLUSION

The exploration and sustainable management of critical minerals demand a transformative approach that unites geology with the full spectrum of modern geospatial technologies. Remote sensing integrated with GIS, geophysics, geochemistry and AI/machine learning has moved the discipline beyond terrain-bound investigation toward predictive, data-driven mineral intelligence. The combined use of multispectral, hyperspectral and radar datasets supported by field spectroscopy enables accurate delineation of alteration zones, structural controls and mineralisation patterns while reducing exploration costs and minimising ecological disturbance. For India, where import dependency on lithium, cobalt and nickel remains a strategic vulnerability and where large tracts of mineral-rich terrain are still under-explored, such advanced workflows form an essential pillar of national mineral security. Embedding these methods within the National Critical Mineral Mission will expand exploration frontiers, ensure reproducible and standardised practices and attract investment aligned with sustainable resource development and circular-economy goals. The convergence of satellite earth observation, UAV based hyperspectral imaging, AI driven prospectivity modelling and open geoscientific data platforms will define the next phase of discovery. Strengthening national spectral libraries, airborne survey programmes and integrated digital platforms will be vital. Ultimately, the fusion of earth observation and resource geology offers not just technological advancement but a strategic pathway to secure energy resilience, enhance economic competitiveness and uphold environmental responsibility in the emerging global energy landscape.

REFERENCES

1. Aitchison, J. C., & Buckley, S. J. (2021). Hyperspectral remote sensing for mineral exploration: Recent developments and challenges. *Ore Geology Reviews*, 134, 104118. https://doi.org/10.1016/j.oregeorev.2021.104118
2. Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, 10(4), 1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005
3. Balaram, V., & Sawant, S. S. (2022). Critical and strategic minerals for India's clean energy transition. *Journal of the Geological Society of India*, 98(4), 365–378. https://doi.org/10.1007/s12594-022-1830-3
4. Bhattacharya, A., & Misra, K. C. (2023). Geospatial integration for sustainable mineral exploration: A review of Indian case studies. *Current Science*, 124(9), 1105–1114.
5. Carranza, E. J. M. (2018). *Geochemical anomaly and mineral prospectivity mapping in GIS* (2nd ed.). Elsevier.
6. Department of Science & Technology (DST), Government of India. (2024). *National Critical Mineral Mission—Framework and Implementation Roadmap (2024–31)*. New Delhi.
7. Down To Earth. (2024, March 15). India is late to the critical minerals party. https://www.downtoearth.org.in/energy/india-is-late-to-the-critical-minerals-party
8. Geological Survey of India (GSI). (2023). *Critical minerals of India: Status, prospects and policy perspectives*. Kolkata: Ministry of Mines.
9. Gupta, R. P. (2017). *Remote sensing geology* (3rd ed.). Springer.
10. Hewson, R. D., Cudahy, T. J., & Huntington, J. F. (2020). Imaging spectroscopy for mineral exploration. *Remote Sensing*, 12(14), 2255. https://doi.org/10.3390/rs12142255
11. International Energy Agency (IEA). (2023). *The Role of Critical Minerals in Clean Energy Transitions*. Paris: IEA.
12. Indian Bureau of Mines (IBM). (2024). *Indian Minerals Yearbook—Critical Minerals*. Nagpur: Ministry of Mines.
13. Jensen, J. R. (2022). *Remote sensing of the environment: An Earth resource perspective* (3rd ed.). Pearson.

14. Mahesh, P., & Raju, K. N. P. (2022). Application of ASTER and Sentinel-2 data for alteration mapping and mineral exploration in Indian shield terrains. *Journal of the Indian Society of Remote Sensing*, 50(8), 1551–1565. https://doi.org/10.1007/s12524-022-01520-x
15. Ministry of Mines, Government of India. (2024). *Policy note on exploration and auction of critical mineral blocks under the MMDR Amendment Act (2023)*. New Delhi.
16. Mishra, A. K., & Singh, V. K. (2023). Integrating hyperspectral, SAR and geochemical data for mineral potential mapping using fuzzy logic and AHP techniques. *Natural Resources Research*, 32, 1441–1462. https://doi.org/10.1007/s11053-023-10211-4
17. NASA Jet Propulsion Laboratory. (2022). *AVIRIS-NG hyperspectral mission overview*. https://avirisng.jpl.nasa.gov
18. Pandey, A., & Sharma, S. (2024). Machine-learning approaches in remote sensing-based mineral prospectivity mapping. *Environmental Earth Sciences*, 83(2), 1–17. https://doi.org/10.1007/s12665-024-11122-3
19. Lehmann, J., et al. (2023). Landsat 8 and ALOS DEM geological mapping reveals the architecture of the giant Mesoproterozoic Kunene Complex anorthosite suite (Angola/Namibia). *Elsevier / ResearchGate*.
20. Pettke, T., & Markl, G. (2020). Critical metals in Earth systems and energy transition. *Elements*, 16(6), 387–392.
21. Rajendran, S., & Nasir, S. (2019). ASTER spectral analysis for mapping of mineral assemblages in arid terrain: Applications for Oman and Indian Shield. *International Journal of Applied Earth Observation and Geoinformation*, 80, 44–57.
22. Shabani, A., et al. (2022). Multi-dimensional data fusion for mineral prospectivity mapping using fuzzy-AHP decision-making method, Kodegan-Basiran region, East Iran. *Minerals*.
23. Singh, S., & Chatterjee, A. (2021). Hyperspectral and radar data integration for structural mapping and mineral exploration: Case studies from Central India. *Geocarto International*, 36(18), 2030–2051. https://doi.org/10.1080/10106049.2020.1782812
24. United States Geological Survey (USGS). (2023). *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*. USGS Professional Paper 1802.
25. World Bank. (2020). *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*. Washington, DC.
26. Ali, S. H., Giurco, D., Arndt, N., et al. (2017). Mineral supply for sustainable development requires resource governance. *Nature*, 543, 367–372. https://doi.org/10.1038/nature21359
27. Bonham-Carter, G. F. (1994). *Geographic Information Systems for Geoscientists: Modelling with GIS*. Oxford: Pergamon Press.
28. Carranza, E. J. M. (2009). *Geochemical anomaly and mineral prospectivity mapping in GIS*. Amsterdam: Elsevier.
29. Cheng, Q. (2012). Multifractal modeling and spatial analysis with GIS for mineral exploration. *Computers & Geosciences*, 42, 1–14. https://doi.org/10.1016/j.cageo.2011.10.009
30. European Commission. (2023). *Critical Raw Materials Act*. Brussels: European Union.
31. Geological Survey of India (GSI). (2023). *Exploration Strategy for Critical and Strategic Minerals*. Kolkata: Ministry of Mines.
32. Goodenough, K. M., Wall, F., & Merriman, D. (2018). The rare earth elements: Demand, global resources, and challenges for resourcing future generations. *Natural Resources Research*, 27, 201–216. https://doi.org/10.1007/s11053-017-9336-5
33. Meinert, L. D., Robinson, G. R., & Nassar, N. T. (2016). Mineral resources and the clean energy transition. *Geosciences*, 6(4), 1–16. https://doi.org/10.3390/geosciences6040046
34. Ministry of Mines, Government of India. (2023). *Report of the Committee on Identification of Critical Minerals*. New Delhi.
35. Ministry of Mines, Government of India. (2024). *National Critical Mineral Mission (NCMM): Framework and Implementation Strategy*. New Delhi.
36. Pour, A. B., & Hashim, M. (2015). Hydrothermal alteration mapping using Landsat-8 data. *Journal of Asian Earth Sciences*, 108, 1–10. https://doi.org/10.1016/j.jseaes.2015.04.021
37. Sabins, F. F. (1999). Remote sensing for mineral exploration. *Ore Geology Reviews*, 14(3–4), 157–183. https://doi.org/10.1016/S0169-1368(99)00007-4
38. van der Meer, F. D., van der Werff, H. M. A., et al. (2012). Multi- and hyperspectral geologic remote sensing: A review. *International Journal of Applied Earth Observation and Geoinformation*, 14(1), 112–128. https://doi.org/10.1016/j.jag.2011.08.002
39. U.S. Geological Survey (USGS). (2024). *Mineral Commodity Summaries 2024*. Washington, DC: U.S. Department of the Interior.

AUTHOR'S BIOGRAPHY

Full name	**Dr. Trupti Bhattacharjee**
Science degree	MSc. PhD
Academic rank	Consultant
Institution	Sapphire Geoconsultants, Nagpur, Maharashtra India

Full name	**Indranil Bhattacharjee**
Science degree	MTech (IIT Kharagpur)
Academic rank	General Manager
Institution	Mining Associates Pvt Ltd, Asansol, West Bengal India