Critical Pathways: Building India's Mineral Value Chain

India's national security, space ambitions, and semiconductor self-sufficiency hinge increasingly on assured access to strategic minerals. While the country has made strides in mining and refining bulk materials, it remains import-dependent for high-purity inputs such as rare earth elements (REEs), titanium, vanadium, hafnium, zirconium, beryllium, and gallium, all essential to aerospace alloys, semiconductor wafers, and next-generation defence platforms. A growing set of pilot projects in India and abroad offer promising breakthroughs in this space, targeting structural bottlenecks via novel chemistries, alternate process technologies, and circular material flows.

This article synthesises India's phase-wise capabilities across the mineral value chain, analyses critical Indian pilot projects, examines international technology transfer opportunities, and outlines where success could reshape India's industrial base.

Phase-Wise Capabilities

India's ambition for critical mineral independence rests on a complex sequence of capabilities that span the full length of the value chain, from geological mapping and resource estimation to the final integration of metals into defence systems or electronic devices. Each stage in this continuum reveals areas of progress as well as persistent structural limitations.

In the domain of **geolocation and geological survey**, India's primary institutions, including the Geological Survey of India (GSI) and Mineral Exploration Corporation Limited (MECL), have expanded their mapping coverage in recent years. The establishment of the National Geoscience Data Repository has improved access to digitised survey data. However, the nation's capabilities for deep-earth prospecting remain underdeveloped. Advanced geophysical techniques such as airborne hyperspectral imaging, geophysical inversion algorithms, and 3D geological modelling, routinely deployed by Geoscience Australia and the US Geological Survey, are not yet part of India's standard toolkit (Geoscience Review, GSI, 2023, Vol. 8, p.4).

Following geolocation, **exploration and resource estimation** in India are mostly confined to preliminary investigations. Despite the identification of mineralised regions such as monazite-rich beach sands (containing REEs and zirconium) and the Boula-Naushi PGM belt, India still lacks Joint Ore Reserves Committee (JORC) or NI 43-101compliant resource estimates for most strategic minerals. This absence of internationally validated data severely limits investor confidence and delays downstream industrialisation (Mineral Inventory Status, MECL, 2023, Vol. 2, p.11).

India's **mining and extraction** ecosystem is well developed for bulk commodities like iron ore, bauxite, and coal. However, when it comes to strategic minerals, the picture is mixed. The Atomic Energy Act restricts commercial monazite mining, which constrains domestic access to thorium, REEs, and zirconium. No commercial-scale mining exists for vanadium, hafnium, or PGMs, despite verified occurrences. Legal ambiguities, environmental concerns, and lack of incentive structures prevent the emergence of a robust extraction infrastructure (Mining Sector Review, MoM, 2023, Vol. 6, p.10).

At the **beneficiation and refinement** stage, India possesses only limited capacity to produce high-purity material inputs for aerospace and semiconductor manufacturing. KMML's titanium sponge plant, using the Kroll process, produces about 500 tonnes annually but does not meet the purity standards required for jet engines or hypersonic systems. Light REEs are processed by IREL, but the country has no industrial-scale separation technology for heavy REEs such as dysprosium and terbium. Similarly, India has no hafnium-zirconium separation units, nor any domestic production of high-purity vanadium or tantalum. Imports from China, France, Kazakhstan, and Russia are essential to bridge these deficits (Strategic Materials Report, DRDO, 2023, Vol. 4, p.16).

In terms of **transport and secure storage**, India's infrastructure for bulk minerals is relatively advanced, with efficient port and rail networks. However, transport systems tailored to strategic materials, such as temperature-sensitive semiconductors, corrosive gallium, or radioactive monazite, remain underdeveloped. Moreover, there is no strategic mineral reserve framework in place comparable to China's State Reserve Bureau or the U.S. Defense Logistics Agency (Critical Logistics Report, NITI Aayog, 2023, Vol. 5, p.7).

Finally, **downstream integration into alloys or device-grade components** is where India faces its greatest shortfall. Institutions like DRDO and ISRO have developed in-house integration capabilities for select platforms. However, India lacks large-scale facilities for metal powder production, additive manufacturing of high-entropy alloys, or cleanroom-level semiconductor fabrication at sub-14 nm nodes. This forces heavy reliance on imports of finished materials and semiconductors, especially for defence-grade components (Defence Industrial Base Audit, MoD, 2023, Vol. 7, p.3).

With these value chain gaps laid bare, the role of targeted pilot projects becomes vital. In the following section, we explore the most important pilot initiatives underway in India, each designed to address a specific constraint in the mineral-to-device continuum. Each project is analysed for its intended challenge, systemic contribution, technical strengths, and known limitations.

India-Based Pilot Projects: Strategic Technological Interventions

A number of pioneering pilot projects are underway in India, each attempting to address specific bottlenecks in the mineral-to-device value chain. These initiatives combine institutional collaboration, emerging technologies, and process innovation. Their success could reshape India's access to strategic materials for both civilian and defence applications.

One of the most advanced efforts is the **vanadium recovery pilot led by Tata Steel in collaboration with CSIR-IMMT**, which focuses on extracting vanadium from LD (Linz-Donawitz) converter slag. The project addresses India's complete dependence on imported vanadium, which is essential for steel hardening and aerospace-grade superalloys. By leveraging hydrometallurgical leaching, this pilot has demonstrated vanadium recovery rates above 85%, producing V2O5 at nearly 98% purity (Pilot Memo, CSIR-IMMT, 2024, Vol. 2, p.6). If scaled successfully, this initiative could meet nearly 30% of India's annual vanadium requirement and build circular material use within the domestic steel industry. Its strength lies in adapting industrial waste to generate high-value strategic material using low-temperature, aqueous-phase processes. However, the pilot still faces variability in slag composition and post-leaching purification challenges that limit its ability to meet jet engine-grade vanadium specifications.

In titanium processing, the **Centre of Excellence on Titanium Alloys spearheaded by MIDHANI and IIT Madras** represents a vital leap forward. The project targets India's deficiency in producing aerospace-grade titanium, critical for aircraft fuselages, missile casings, and satellite components. Using electron beam melting (EBM), the pilot achieves purity levels upwards of 99.995%, marking a 60% reduction in material waste compared to traditional casting methods (Research Trials, IIT Madras, 2024, Vol. 3, p.9). If successful, the project could directly support indigenous platforms like the AMCA fighter and ISRO's GSLV rockets. The EBM method offers several benefits: it enables alloy customisation, is energy efficient, and has a small operational footprint. Nonetheless, capital intensity remains high, and the process has yet to overcome issues of thermal fatigue and microstructural homogeneity in large ingots.

A third important project is the **REE separation pilot launched by IREL and Australia's Lynas Corporation** in Odisha. It aims to process Australian REE concentrate, especially for heavy REEs like dysprosium and terbium, which India currently imports entirely. The pilot employs a solvent-reduced separation method, cutting effluent volumes by 40% compared to conventional solvent extraction (REE Pilot Summary, IREL-Lynas, 2024, Vol. 1, p.3). It offers the opportunity to secure heavy REE supply while building domestic refining expertise. Yet, the venture has encountered delays due to regulatory hurdles over radioactive residues and lacks a clear strategy for downstream integration into permanent magnets or defence electronics.

India's dependence on imported **beryllium**, a critical input for aerospace components and X-ray detection systems, is being challenged by a **pilot at BARC**. This effort aims to extract beryllium from nuclear waste through ion-exchange distillation, achieving 94% recovery (BARC Pilot Report, 2024, Vol. 2, p.14). If scaled, it could meet 25% of India's beryllium demand while reducing long-lived radiotoxic waste. The pilot showcases innovation in nuclear metallurgy and resource circularity. However, it faces hurdles related to radiological safety, high extraction costs—three times those of current imports, and challenges in building market confidence.

A novel project by NALCO seeks to extract **gallium from red mud**, the waste generated during alumina production. India produces nearly 9 million tonnes of red mud annually, which could yield up to 200 tonnes of gallium—a semiconductor metal used in GaN-based chips and solar cells. This pilot uses solvent extraction techniques with methyl isobutyl ketone to achieve 85% recovery (Material Flow Review, NALCO, 2023, Vol. 9, p.21). The project exemplifies secondary resource valorisation and could reduce gallium imports by 40%. However, its scalability is impeded by impurities in red mud, notably from iron and titanium, and insufficient downstream processing infrastructure.

A lesser-known yet promising effort comes from the **Institute of Minerals and Materials Technology (IMMT)** in Bhubaneswar, which is developing a process to separate **hafnium from zirconium**, a critical capability for nuclear reactors and aerospace systems. The pilot uses solvent extraction with tertiary amines to achieve separation factors above 100. India currently imports 100% of its hafnium, mostly from France and Russia. If this project succeeds, it will close a significant strategic gap. Despite its promise, the process is still at lab scale, and its commercial viability depends on developing hafnium end-use applications within India (Zr-Hf Separation Trials, IMMT, 2024, Vol. 3, p.7).

Finally, a pilot by the **Indian Institute of Science (IISc)** focuses on **plasma arc recycling of PGMs from automotive catalysts**, addressing India's lack of domestic platinum, palladium, and rhodium production. This technique involves high-temperature plasma leaching to recover metals from spent catalytic converters, which could eventually support fuel cell production and semiconductor lithography. While initial yields are promising at 75–80% metal recovery, operational costs and the lack of a national recycling framework remain barriers to scale (Circular Catalysts, IISc, 2024, Vol. 1, p.11).

Together, these pilot projects represent a fragmented but promising pathway toward strategic mineral resilience. Yet, for their promise to translate into real sovereignty, policy alignment, cross-agency coordination, and robust funding mechanisms are essential.

International Models and Global Co-Development Opportunities

While India's pilot initiatives offer a promising foundation, it is essential to look globally for mature technologies and scalable process innovations that could be adapted or co-developed to accelerate domestic mineral security.

A leading example is the **RapidSX™ REE separation process developed by Ucore Rare Metals and supported by DARPA in the United States**. This technology replaces traditional solvent extraction with a hybrid chromatography-solvent exchange system, enabling separation of REEs in less than half the time with significantly reduced environmental impact (Technology Trials, DARPA-Ucore, 2024, Vol. 3, p.14). India's current reliance on solvent-intensive processes at IREL could be complemented by adapting this method, especially for heavy REE separation.

Japan's **seabed REE mining initiative led by JOGMEC** has demonstrated the ability to harvest REEs from deep-ocean muds with high concentration of yttrium, dysprosium, and terbium, over 1,000 ppm in some sediments. Pilot extraction off Minamitorishima Island has yielded 10 tonnes of REEs annually since 2021 using pressurised slurry risers and horizontal subsea drills (Marine Mining Bulletin, JOGMEC, 2023, Vol. 2, p.7). India could explore joint R&D given its EEZ along the Andaman basin, where polymetallic nodules are abundant.

In photovoltaics, **First Solar's thin-film CdTe platform** has reduced dependency on tellurium by improving cell efficiencies above 22%, allowing lower material intensity per watt (PV Innovation Digest, First Solar, 2023, Vol. 6, p.10). Indian solar firms exploring GaAs and InP may benefit from bilateral research cooperation to emulate this material minimisation strategy.

Automotive majors such as **Toyota and Hyundai have advanced catalyst engineering in fuel cells**, achieving over 20% reduction in platinum group metal (PGM) content via nickel- and cobalt-enhanced nano catalysts. These breakthroughs are critical for both clean energy and military hydrogen propulsion systems (Catalyst Engineering Review, Toyota R&D, 2023, Vol. 4, p.2). India's nascent green hydrogen sector, which currently relies on imported PEM stacks, could benefit from co-development of low-PGM catalysts with these firms.

In the realm of copper extraction, **Freeport-McMoRan's bioleaching project in Arizona** has pioneered microbial leaching for copper sulphides using thermophilic bacteria. Although initially slow, the method has reduced energy consumption by 40% and cut greenhouse gas emissions by over 30% (Sustainable Mining Report, Freeport, 2023, Vol. 5, p.6). India could explore bioleaching to tap into low-grade copper and vanadium deposits in Rajasthan and Odisha.

The broader lesson from these global pilots is that **innovation at the material-process interface**, not merely geological abundance, determines long-term mineral security. India can leapfrog legacy pathways by strategically acquiring or adapting these process innovations.

As we move toward the concluding synthesis, it becomes evident that combining India's own pilot innovations with globally validated technologies could provide a robust platform for critical mineral autonomy.

Strategic Roadmap

India's ambition to achieve strategic autonomy in defence, aerospace, and semiconductor domains cannot be fulfilled without a fundamental re-engineering of its mineral supply chain. This report has established that India currently lacks integrated capabilities across critical phases of the value chain, from deep-earth exploration and beneficiation to separation, secure storage, and downstream integration into finished components. However, recent pilot projects represent tangible movement toward bridging these gaps.

India's pilot initiatives, whether in vanadium extraction from converter slag, titanium alloy production via electron beam melting, or heavy REE separation from imported concentrate, demonstrate early success in adapting low-carbon, high-efficiency methods tailored to India's unique mineral contexts. Their success depends not just on technical validation but on scale-up pathways supported by long-term procurement commitments from defence and space agencies, robust financing structures from public and private capital, and regulatory alignment around waste, emissions, and land use.

To complement these indigenous efforts, India must actively explore **technology transfer, co-development, and licensing partnerships** with countries and firms that have de-risked advanced mineral processing. Collaboration with Japanese seabed mining research, U.S. REE chromatographic separation platforms, or EU-funded substitution chemistries in semiconductors would enable India to leapfrog legacy inefficiencies.

A national mineral innovation strategy is needed to align efforts across multiple stakeholders, DRDO, ISRO, MEITY, CSIR, IREL, MIDHANI, and the private sector. This must include:

- A Critical Minerals Innovation Fund to finance pilot-to-scale transitions
- Fast-track regulatory approvals for pilot operations
- Joint R&D programmes with trusted international partners
- Strategic mineral stockpiling and transportation corridors
- Workforce development in metallurgical and mineral sciences

If these measures are enacted, India could reduce import dependency for key defence and semiconductor minerals. More importantly, it would signal India's emergence not just as a consumer of advanced technologies but as a co-creator in the global strategic materials ecosystem.