India's Nickel-Cobalt Self-Reliance: Integrating Geological Frameworks, Lateritic Resources, Deep Ocean Mission, and National Critical Minerals Mission Pathways

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Abstract:
India faces significant vulnerabilities in its supply chains for nickel and cobalt, critical metals essential for stainless steel, high-temperature alloys, and lithium-ion batteries in the clean energy transition. Despite substantial domestic lateritic resources in regions like Odisha and Jharkhand, and potential offshore polymetallic nodules via the Deep Ocean Mission, India remains nearly 100% import-dependent. This article synthesizes global and Indian geological frameworks, resource distributions, demand-supply imbalances, and strategic interventions under the National Critical Minerals Mission (NCMM). It emphasizes four pillars: global occurrence of magmatic sulfide, laterite, and sediment-hosted copper–cobalt systems, and polymetallic nodules geometallurgical characterization for high-pressure acid leaching (HPAL) and alternative flowsheets, integration of seafloor data with onshore exploration, and alignment with NCMM pathways including recycling and overseas acquisitions. Projections indicate demand growth to 170 kt nickel and 20–30 kt cobalt by 2030, underscoring the need for accelerated exploration, processing parks, and circular economy initiatives. Challenges such as long project lead times and geopolitical risks are addressed, with recommendations for policy enhancements to achieve 30–50% self-reliance by 2035.

Keywords: Nickel-cobalt reserves and resources, self-reliance, Critical minerals India, National Critical Minerals Mission (NCMM), Lateritic nickel deposits, Deep Ocean Mission polymetallic nodules, High-Pressure Acid Leaching (HPAL), Battery-grade nickel cobalt, India import dependency critical minerals, EV battery supply chain India

1. INTRODUCTION

Nickel and cobalt are critical to clean-energy and industrial systems through their use in austenitic stainless steels, high-temperature alloys, and high-nickel cathodes (NMC, NCA) in lithium-ion batteries (IEA, 2025; Naldrett, 2004). Their geological scarcity, concentration of mining and refining in a few countries such as Indonesia, the DRC, and China, and long mine development lead times together create significant supply-chain vulnerabilities for resource-importing economies (Cobalt Institute, 2024; Darton Commodities, 2024; USGS, 2025a,b,c).

India, the world's third-largest energy consumer, has committed to net-zero emissions by 2070 and targets 30% electric-vehicle (EV) penetration by 2030, implying steep increases in Ni–Co demand (CEEW, 2025; IEA, 2025). Yet primary nickel output (~7.5 kt/year) and cobalt production (≈0 kt/year) are negligible, and nearly all supply is imported as refined intermediates from Indonesia–China–DRC-linked supply chains, despite substantial lateritic nickel in Odisha and associated cobalt in Odisha and Jharkhand (IBM, 2024; GSI, 2024; Ministry of Mines, 2025a). The NCMM, launched in 2025, seeks to address this gap through enhanced exploration, advanced processing (including HPAL), recycling, and integration of offshore polymetallic nodules via the Deep Ocean Mission (Ministry of Mines, 2025b; NIOT, 2025).

This article synthesizes global and Indian Ni–Co geological frameworks, resource distributions, and demand–supply imbalances, and then extends existing work by explicitly incorporating four methodological and strategic pillars: (a) global occurrences resources and reserve of nickel and coblat (b) geometallurgical characterisation to de-risk HPAL and alternative flowsheets; (c) integration of Deep Ocean Mission seafloor data with onshore exploration; and (d) alignment with NCMM-based Ni–Co self-reliance pathways (GSI, 2024; Ministry of Mines, 2025b; NIOT, 2025; Çoban & Ahmet, 2024).

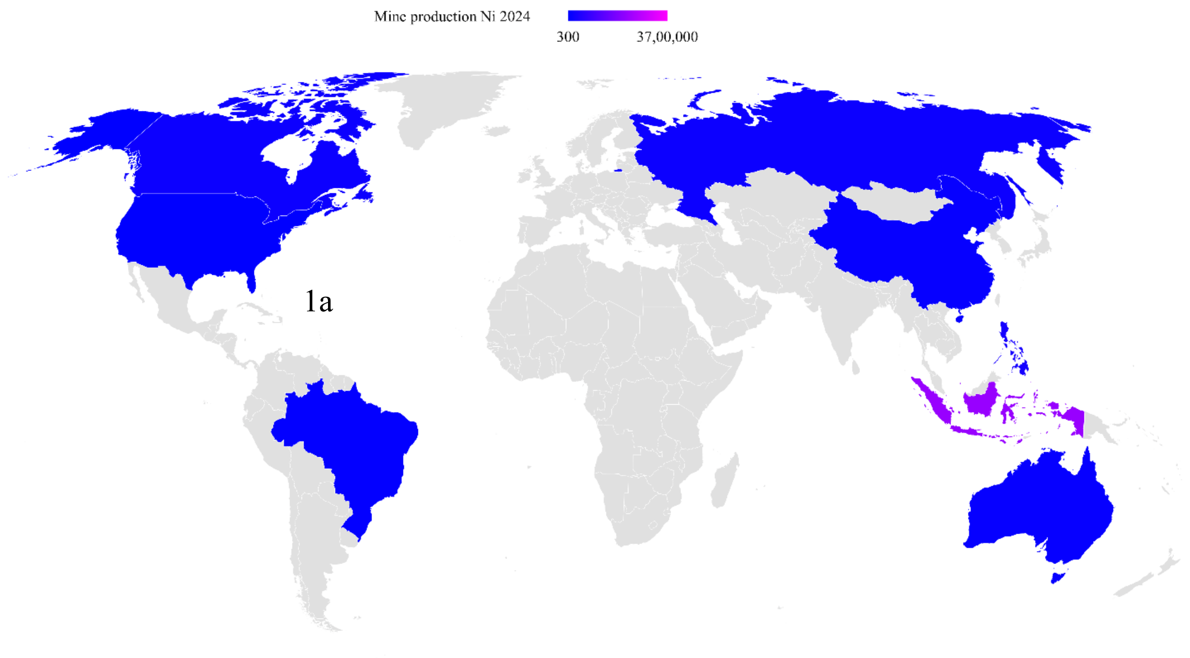
2. GEOLOGICAL FRAMEWORKS OF NICKEL AND COBALT DEPOSITS

Nickel and cobalt occur predominantly in magmatic sulfide, laterite, and sediment-hosted copper–cobalt systems, with additional potential in polymetallic nodules and Co-rich ferromanganese crusts (Arndt, 2011; Hein, 2020) (Figure 1a and 1b). Magmatic Ni–Cu–Co sulfide deposits form in mafic–ultramafic intrusions where sulfur-saturated magmas exsolve immiscible sulfide liquids that scavenge Ni, Co, Cu, and platinum-group elements, as exemplified by Norilsk and Sudbury (Barnes, 2016; Naldrett, 2004).

Lateritic Ni–Co deposits develop through deep weathering of ultramafic rocks in tropical to subtropical climates, producing a vertical zoning from Fe-rich limonite (commonly Co-enriched) to Ni-rich saprolite/clay–serpentinite overlying ultramafic bedrock (Butt, 2016; USGS, 2025a, c) (Table 1, Figure 2a, 2b). Sediment-hosted Cu–Co deposits such as those in the Central African Copperbelt supply most of the world's mined cobalt as a by-product of copper, while polymetallic nodules on the ocean floor contain substantial Ni–Co–Mn endowment that is presently pre-commercial but strategically important (Hein, 2020; Hitzman, 2017; Slack, 2013).

Table 1: Depositional settings and approximate share of global Ni–Co resources (adapted from Arndt, 2011; Hein, 2020).

Deposit type	Key geological features	Approximate share (%)
Magmatic sulfide	Mafic–ultramafic intrusions; immiscible sulfide liquids	30
Laterite	Intense weathering; limonite–saprolite zoning	60
Sediment-hosted Cu–Co	Stratiform Cu–Co in sedimentary basins	10



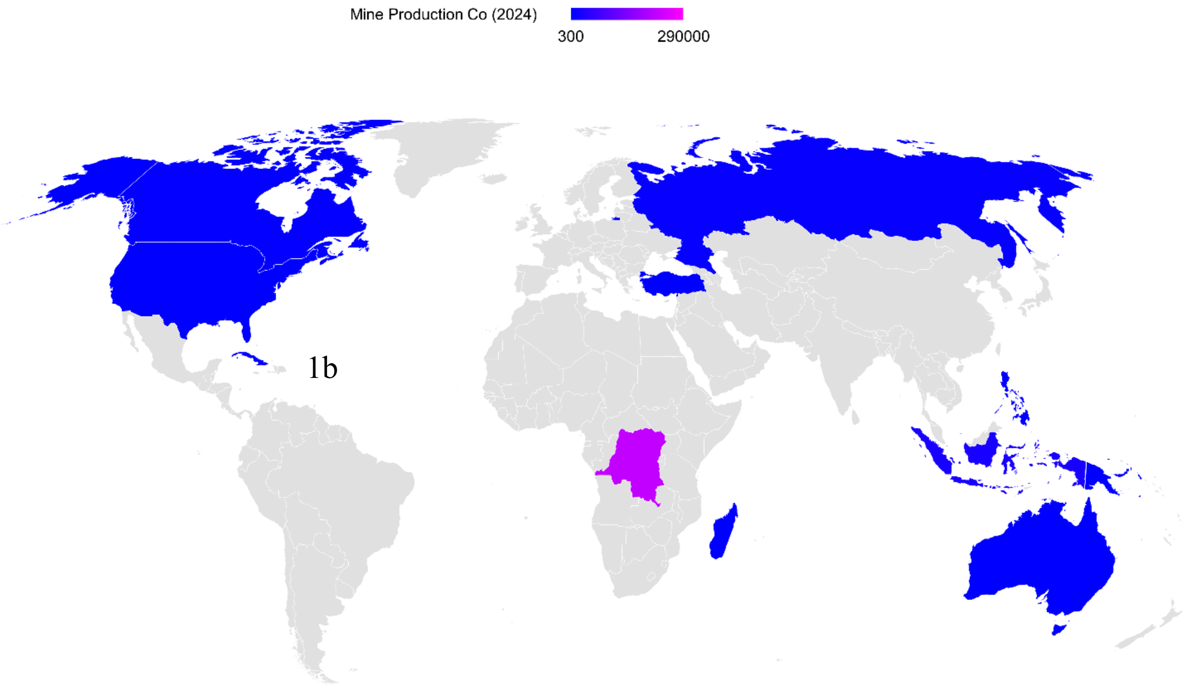


Figure 1. Global Distribution of Nickel and Cobalt Deposits. 1a Ni and 1b Co maps (Based on USGS 2025a, c).

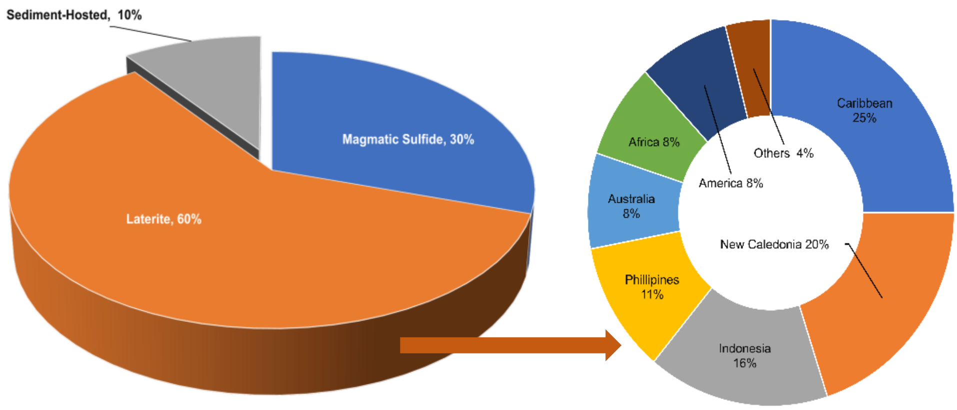


Figure 2: Pie Chart of Deposit Types (Fig. 2a). Depositional settings and approximate share of global Ni–Co resources (adapted from Arndt, 2011; Hein, 2020). and Figure 2b World Lateritic Nickel Resources Distribution (INSG 2024).

2a 2b

3. GLOBAL AND INDIAN NI–CO RESOURCE DYNAMICS

Global nickel reserves are ~130 Mt within a resource base of ~350 Mt, dominated by Indonesia (~55 Mt; 42%) and Australia (~24 Mt; 18%) (International Nickel Study Group, 2024; USGS, 2025). Cobalt reserves are ~11 Mt within ~25 Mt identified resources, more than half of which are located in the DRC, while China refines roughly two-thirds of cobalt intermediates into battery-grade chemicals (Cobalt Institute, 2024; Darton Commodities, 2024; USGS, 2025) (Table 2, Figure 3).

Nickel demand is projected to rise from 3.9 Mt in 2025 to 4.8 Mt in 2030, driven by stainless steel and batteries, with emerging deficits linked to 10–12-year project lead times (CRU Group, 2024; S&P Global, 2025; Wood Mackenzie, 2024). Cobalt demand is expected to grow from ~300 kt to ~400 kt over the same period, with short-term oversupply tightening as ESG constraints and under-investment limit new projects (Benchmark Mineral Intelligence, 2025a,b,c; Cobalt Institute, 2025) (Table 2, Figure 3).

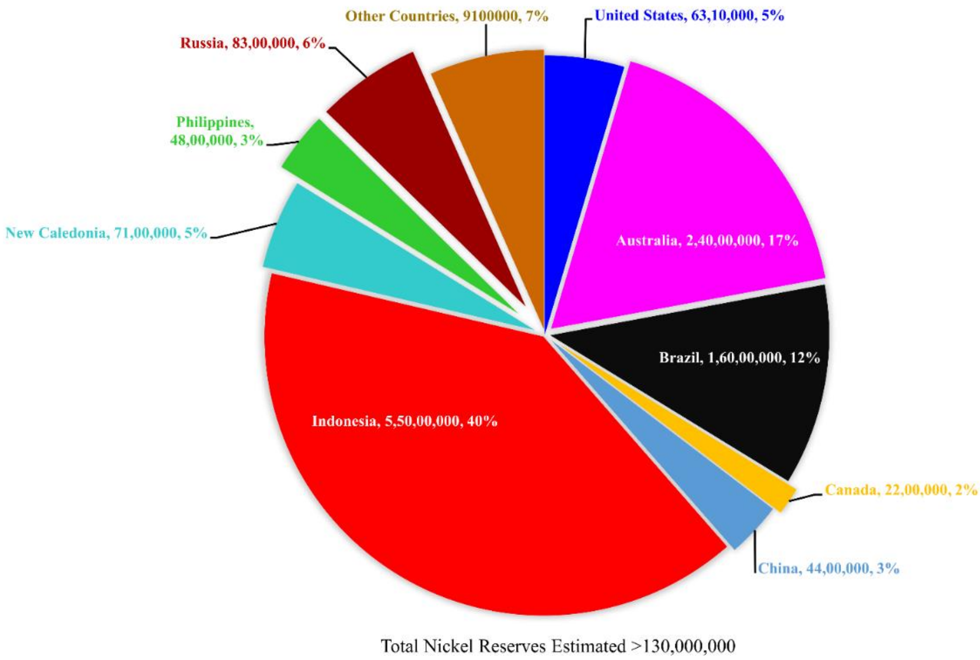
India's nickel resources are ~189 Mt of ore, ~92% in laterites of the Sukinda Valley (Das et al 1999), with modest reserves (~2–3 Mt) and mine production of ~7.5 kt/year from Vedanta's Nicomet facility, while 44.9 Mt of Co-bearing ore are largely undeveloped (GSI, 2024; IBM, 2024; Ministry of Mines, 2025a). Nickel consumption of ~85 kt/year in 2025 is projected to reach ~170 kt in 2030 and ~300 kt by 2040, implying an import gap of 77.5 kt in 2025 rising to ~160 kt in 2030 and ~250 kt in 2040 (CEEW, 2025; IEEFA, 2025; Ministry of Mines, 2025a). Cobalt demand of 10–15 kt/year is fully import-dependent and closely tied to NMC-based EV adoption (CEEW, 2025; IEA, 2025; USGS, 2025).

Table 2: Global Nickel Mine Production and Reserves (USGS 2025c).

Countries	Mine Production 2024	Reserves
United States	8,000	310,000
Australia	110,000	24,000,000
Brazil	77,000	16,000,000
Canada	190,000	2,200,000
China	120,000	4,400,000
Indonesia	2,200,000	55,000,000
New Caledonia	110,000	7,100,000
Philippines	330,000	4,800,000
Russia	210,000	8,300,000
Other Countries	300.000	>9.100.000
World Total (rounded)	3,700,000	>130,000,000

Table 3: Global Cobalt Mine Production and Reserves (USGS 2025a).

Countries	Mine Production Co (2024)	Reserves
United States	300	70,000
Australia	3,600	10,17,00,000
Canada	4,500	2,20,000
Congo (Kinshasa)	2,20,000	60,00,000
Cuba	3,500	5,00,000
Indonesia	28,000	6,40,000
Madagascar	2,600	1,00,000
New Caledonia[11]	1,500	NA
Papua New Guinea	2,800	62,000
Philippines	3,800	2,60,000
Russia	8,700	2,50,000
Turkey	2,700	91,000
Other countries	6,200	8,00,000
World total (rounded)	2,90,000	1,10,00,000



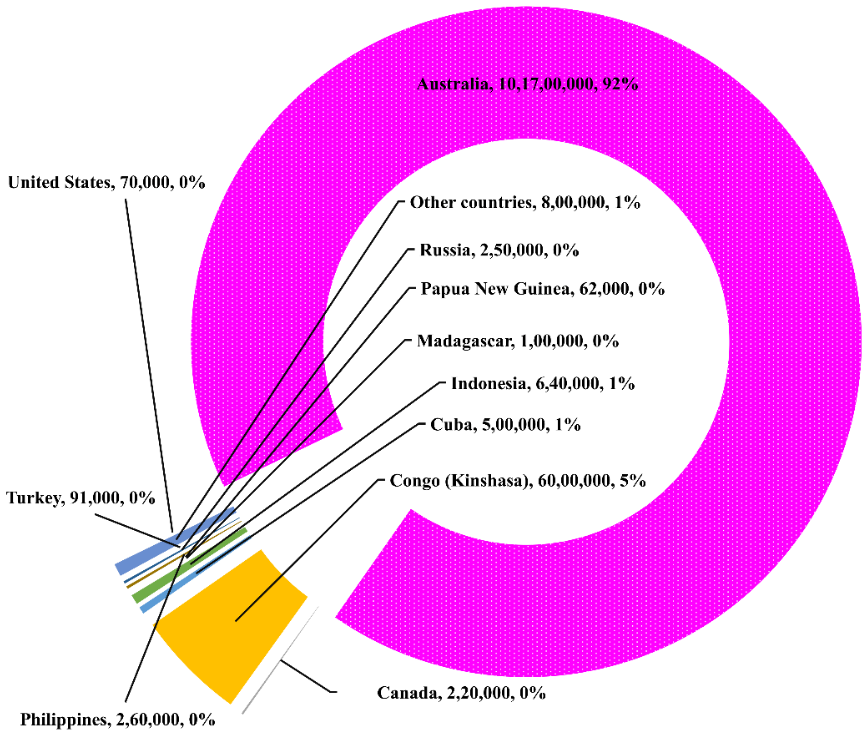


Figure 3. Global Ni–Co Reserves Pie Chart, 3a for Nickel and 3b Doughnut Chart for Cobalt (USGS 2025a, c).

4. INDIA'S RESOURCES OF NICKEL AND COBALT

India's nickel resources are estimated at 189 million tonnes, primarily in Odisha's Sukinda Valley (92%), with minor deposits in Jharkhand, Karnataka, and Rajasthan (GSI, 2024,). Nickel occurs as oxides and sulfides, often associated with chromite (IBM, 2024a,b). Production is limited, with Odisha as the primary source, and India relies heavily on imports (Ministry of Mines, 2025a, Som 2002, Sukla et al 2009).

Cobalt resources total ~44.9 million tonnes, mainly in Odisha and Jharkhand, associated with nickel and copper deposits (GSI, 2024a, b, c, d). India lacks domestic cobalt production, resulting in complete import dependency (IBM, 2024a,b). Polymetallic nodules in the Indian Ocean offer future potential (NIOT, 2024).

Table 3: Distribution of Nickel Resources in India.

State	Nickel Resources (%)
Odisha	92
Jharkhand	5
Others	3

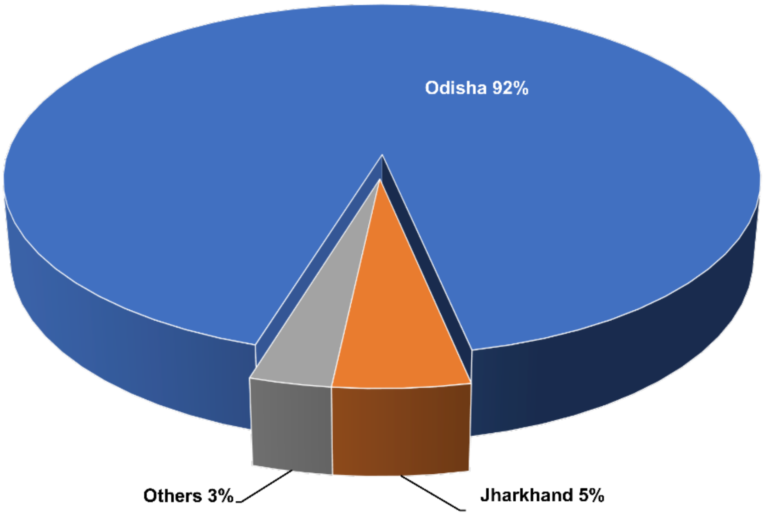


Figure 4: Pie Chart of Indian Nickel Resources pie chart can be generated using the data above to visualize the dominance of Odisha in India's nickel resources.

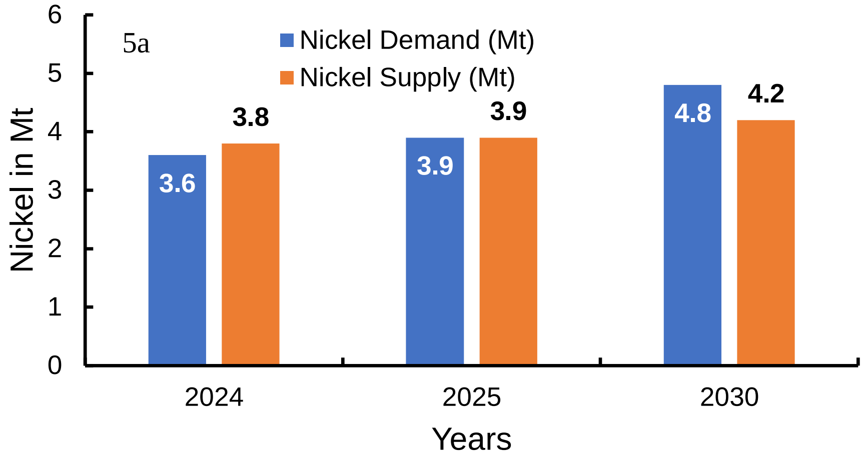
5. GLOBAL DEMAND-SUPPLY AND GAPS

Nickel demand, driven by stainless steel (70%) and EV batteries, is projected at 3.9 million tonnes in 2025, growing at 2.8% annually (CRU Group, 2025). Supply matches demand at 3.9 million tonnes, but deficits are forecast by 2030 due to 12-year mine development lead times (Wood Mackenzie, 2024; Benchmark Mineral Intelligence, 2025).

Cobalt demand, primarily for batteries, is expected to reach 300,000 tonnes in 2025, with a 50% increase by 2040 (Cobalt Institute, 2025). A 2025 oversupply of ~25,000 tonnes is projected, but the DRC's 74% production share and China's 68% refining dominance create vulnerabilities (IEA, 2024; Ellen MacArthur Foundation, 2024).

Table 4: Demand-Supply Forecast (2024-2030).

Year	Nickel Demand (Mt)	Nickel Supply (Mt)	Cobalt Demand (kt)	Cobalt Supply (kt)
2024	3.6	3.8	250	290
2025	3.9	3.9	300	325
2030	4.8	4.2	400	350



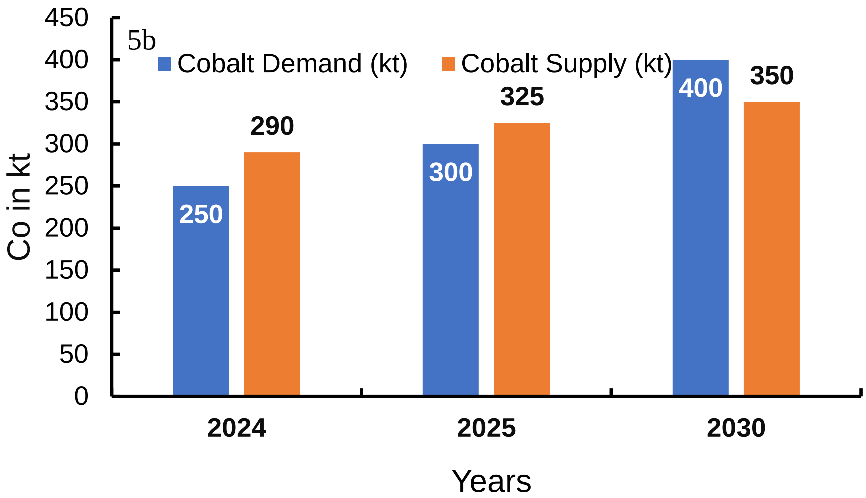


Figure 5: Bar Chart of Demand-Supply Trends for Nickel (5a) and for Cobalt 5b. Nickel and cobalt demand vs. supply from 2024 to 2030, highlighting potential shortages by 2030.

6. FUTURE PLANS AND STRATEGIES TO TACKLE DEFICIENCIES

Global strategies focus on diversification, recycling, and technological innovation. Recycling could sustain nickel and cobalt supply for centuries, while cobalt-free batteries (e.g., sodium-ion) reduce dependency (Battery Council International, 2025; The Metals Company, 2024). Investments in Australia and seafloor mining aim to diversify supply away from DRC and Indonesia (Ministry of Mines, 2025a).

India’s National Critical Mineral Mission (2025) targets self-reliance through 81 exploration projects, deep-sea mining in the Indian Ocean, and international partnerships with Australia and Latin America (NIOT, 2025; Government of India, 2023). The 2023 Mines and Minerals Act amendments and $4 billion investments bolster domestic production (NITI Aayog, 2024). Recycling hubs and Production-Linked Incentive (PLI) schemes are under consideration.

Table 5: Strategic Interventions for Nickel and Cobalt Supply global and Indian strategies.

Strategy Category	Global Initiatives	Indian Initiatives
Exploration	Investments in Australia, Seafloor Mining	81 Exploration Projects, Deep Ocean Mission
Recycling	Battery Recycling Programs	Proposed Recycling Hubs
Policy Reforms	-	Mines Act 2023, $4B Investment, PLI Schemes
International Partnerships	-	Collaborations with Australia, Latin America

India's National Critical Minerals Mission (NCMM), approved by the Union Cabinet on January 29, 2025, constitutes a comprehensive strategic framework to secure domestic supply chains for 30 designated critical minerals, including nickel and cobalt, which are essential for stainless steel production, lithium-ion battery cathodes (NMC and NCA chemistries), and industrial applications central to the country's energy transition and net-zero ambitions by 2070. The mission carries a total outlay of ₹34,300 crore over seven years (FY 2024–25 to FY 2030–31), comprising ₹16,300 crore from government funds and ₹18,000 crore from public sector undertakings (PSUs) and private sector contributions (Press Information Bureau, 2025a). Nickel and cobalt are prioritized due to India's near-total import dependency—approximately 100% for both metals—despite substantial domestic resources: nickel at ~189 million tonnes (primarily laterites in Odisha) and cobalt at ~44.9 million tonnes (largely associated with nickel and copper deposits) (USGS, 2025a,b,c; IEEFA, 2025).

The NCMM is structured around five core pillars: accelerated domestic exploration, overseas asset acquisition, downstream processing development, recycling scale-up, and human capital & financial support. Governance is vested in an Empowered Committee on Critical Minerals, chaired by the Secretary of Mines, with representation from the Geological Survey of India (GSI), PSUs (e.g., NALCO, Hindustan Copper), private industry, and NITI Aayog, ensuring coordinated execution across ministries (Ministry of Mines, 2025a). The mission targets 1,200 domestic exploration projects, acquisition of 50 overseas mining assets, establishment of five Critical Mineral Processing Parks, and recycling capacity of 270 ktpa by 2030–31, with annual progress tracked via a digital monitoring dashboard (Press Information Bureau, 2025b).

Implementation unfolds in three phases. The Foundation Phase (FY 2024–25 to FY 2025–26) focuses on exploration and institutional setup: GSI has launched 1,200 exploration projects (227 in FY 2025–26), with 368 completed and 195 ongoing as of late 2025; 100+ critical mineral blocks have been identified for auction under the amended Mines and Minerals (Development and Regulation) Act; and the NCMM Outreach Forum was established in June 2025 to facilitate industry collaboration. Pilot projects for unconventional sources (e.g., tailings and offshore nodules) have been funded at ₹100 crore (Ministry of Mines, 2025b). The Acceleration Phase (FY 2026–27 to FY 2028–29) emphasizes overseas acquisition and processing infrastructure, targeting 30 international assets and five dedicated parks (notably in Odisha and Gujarat), alongside R&D for 500 patents and skilling of 10,000 personnel. The Consolidation Phase (FY 2029–30 to FY 2030–31) aims for full value-chain integration, strategic stockpiling (60–180 days), and commercial-scale recycling yielding 40 ktpa of recovered critical metals annually (Press Information Bureau, 2025a).

For nickel and cobalt specifically, the mission integrates targeted strategies across all pillars. Domestic exploration prioritizes Odisha's laterite resources (175 Mt nickel) and associated cobalt deposits in Jharkhand, alongside offshore polymetallic nodules rich in cobalt, nickel, and manganese (10 pilots funded). Overseas acquisition is led by Khanij Bidesh India Ltd (KABIL), which has pursued nickel-cobalt assets in Australia (MoU 2022), Argentina (lithium-nickel off-take), and Zambia's copper-cobalt belt, supported by multilateral frameworks such as the Minerals Security Partnership (MSP) and Quadrilateral Security Dialogue (Quad) (Observer Research Foundation, 2025). Processing development includes high-pressure acid leaching (HPAL) facilities within the planned parks to produce battery-grade nickel sulfate and cobalt sulfate, complemented by Centres of Excellence (launched April 2025) driving research into low-cobalt cathode alternatives (e.g., LFP, LMFP) and efficient recovery technologies.

Recycling forms a high-impact pillar, with a ₹1,500 crore incentive scheme finalized in 2025 to scale capacity to 270 ktpa by 2030–31. Updated Battery Waste Management Rules enforce Extended Producer Responsibility (EPR) with 90%+ recovery targets, customs exemptions on cobalt/nickel waste, and support for leading recyclers (Attero, Lohum, Recyclekaro) achieving 90–95% recovery rates via hydrometallurgy. This secondary supply pathway is projected to meet 15–30% of demand by 2030 (NITI Aayog, 2022; IEEFA, 2025).

Despite robust planning, challenges include long gestation periods for mining projects (5–10 years), environmental and social concerns in tribal areas, limited current refining capacity, and heavy global concentration risks (Indonesia for nickel, DRC/China for cobalt). Overcoming these requires accelerated execution of NCMM milestones, increased private-sector participation, robust multilateral partnerships, and continued policy support for recycling and innovation.

The NCMM provides India with a structured, multi-decade pathway to transition from near-total import dependence to 30–50% self-reliance in nickel and cobalt by 2035, safeguarding supply chains, supporting EV-led industrial growth, and advancing long-term energy security objectives.

7. GEOMETALLURGICAL CHARACTERISATION TO DE-RISK HPAL, TECHNOLOGY FOR BATTERY-GRADE NICKEL AND COBALT AND ALTERNATIVE FLOWSHEETS (STATE-OF-THE-ART AS OF JANUARY 08, 2026)

7.1. High-Pressure Acid Leaching (HPAL): In-Depth Technical Review of the Dominant

High-pressure acid leaching (HPAL) remains the only commercially mature hydrometallurgical technology capable of economically converting low-grade nickel laterite ores — particularly the limonite fraction — into high-purity Class-1 nickel and cobalt suitable for lithium-ion battery cathodes (NMC, NCA). Indonesia continues to drive the overwhelming majority of new capacity, with several large-scale projects in full operation, ramp-up phase, or advanced construction, while legacy operations persist in Australia and a few other regions (Project Blue, 2025; Wood Mackenzie, 2023, Mamyrbayeva et. al. 2024).

7.2. Fundamental Chemistry and Thermodynamics

HPAL selectively extracts nickel and cobalt from goethite (FeOOH), asbolane ($(Ni,Co)_xMnO_2{\cdot}nH_2O$), and nontronite using concentrated sulfuric acid at temperatures of 245–270 °C and total pressures of 44–54 bar. The key simplified reactions are:

(1) $NiO + H_2SO_4 \rightarrow NiSO_4 + H_2O$

(2) $CoO + H_2SO_4 \rightarrow CoSO_4 + H_2O$

(3) $FeOOH + 3H_2SO_4 \rightarrow Fe(SO_4)_3 + 4H_2O$ (undesirable, acid-consuming side reaction)

The process is thermodynamically designed so that dissolved iron and aluminium re-precipitate at high temperature as stable hematite (Fe_2O_3) and alunite or basic aluminium sulfate. This precipitation step is critical: it dramatically reduces net sulfuric acid consumption and produces a relatively clean pregnant leach solution (PLS) typically assaying 3–7 g/L Ni, 0.2–0.6 g/L Co, <1 g/L Fe, and 30–50 g/L free H_2SO_4 (Whittington & Muir, 2000).

7.3. Modern HPAL Flowsheet (2024–2026 Standard)

The current “Gen-3” HPAL flowsheet, widely implemented across Indonesia’s major industrial parks (IMIP, IWIP, Obi Island), incorporates numerous engineering, materials, and operational improvements that have largely resolved the reliability, scaling, and cost problems that plagued earlier generations of plants commissioned in the 1990s and early 2000s. The principal stages, typical equipment, operating conditions, and performance indicators of the contemporary flowsheet are presented in the table 6.

Table 6: Stages, typical equipment operating conditions and performance indicators

Stage	**Key Equipment & Conditions (2025–2026)**	**Purpose & Performance**
Ore Preparation	High-pressure grinding rolls (HPGR) + wet screening	Liberate limonite (<1 mm); reject saprolite & high-magnesia fractions
Preheating	4–6 stage flash train + live steam injection	Raise slurry to 180–220 °C while recovering flash steam
Autoclave Leaching	Titanium-lined horizontal agitated autoclaves (4–6 compartments, 1,200–2,000 m³ each)	245–270 °C, 44–54 bar, 45–70 min residence, 92–96 % Ni extraction, 90–95 % Co

Flash Let-Down & Cooling	6–8 stage flash vessels + shell-and-tube coolers	Recover 70–85 % of input heat; depressurise to atmospheric
Counter-Current Decantation (CCD) Thickening	6–8 thickeners in series	Wash residue; produce clarified PLS at 4–7 g/L Ni
Neutralisation & Impurity Removal	Limestone + lime + oxidising agent (air/SO_2)	Precipitate Fe, Al, Cr as hydroxides (<5 mg/L residual in final PLS)
Mixed Hydroxide Precipitate (MHP) Route (dominant in Indonesia)	NaOH/MgO precipitation at pH 8–9	Produce MHP containing 35–55 % Ni + 1–5 % Co (preferred intermediate)
Mixed Sulfide Precipitate (MSP) Route (legacy)	H_2S precipitation	Produce MSP containing 55–60 % Ni + Co (higher capital cost)
Solvent Extraction & Refining (optional for Class-1)	Cyanex 301/272 or P507 + electrowinning/crystallisation	Battery-grade $NiSO_4·6H_2O$ (≥22.2 % Ni) & $CoSO_4·7H_2O$ (≥20.8 % Co)

7.4. 2025–2026 Design Improvements vs. Early Commercial Plants

Early commercial HPAL facilities suffered from severe scaling, high acid consumption, poor heat integration, frequent autoclave downtime, and relatively low metal recoveries. Current Gen-3 plants have systematically addressed these issues through improved process control, equipment materials, and operational strategies, as summarised in the comparison table 7.

Table 7: Generation 3 Plants improved process control, equipment materials and operating strategies

Issue in Early Plants (1990s–early 2000s)	**Current Solution (Gen-3 HPAL, 2025–2026)**
Severe scaling (alunite, anhydrite)	Controlled acid injection + seed recycling + optimised temperature profile
High acid consumption (>400 kg/t ore)	Pre-rejection of saprolite/high-Mg fractions + HPGR; 250–280 kg/t now typical
Poor heat recovery	Extended 6–8 stage flash trains → 75–85 % heat recovery
Titanium corrosion & frequent maintenance	Use of Grade-2/Grade-7 titanium + advanced welding + robotic cleaning
Low nickel recovery (70–80 %)	93–96 % Ni and 90–95 % Co extraction now routine
Environmental incidents (e.g., Ramu spills)	Dry-stack tailings + zero-liquid discharge design in new facilities

7.5. Operating and Committed HPAL Projects (January 08, 2026)

Indonesia has rapidly become the epicentre of global HPAL capacity expansion. The major operating, ramp-up, and late-construction projects are listed in Table 8. Total committed new HPAL-derived nickel capacity is projected to exceed 850–900 ktpa by 2028, with the vast majority located in Indonesia (Project Blue, 2025).

Table 8: Major Operating, ramp-up and late construction projects in Indonesia

Project / Owner	**Location**	**Status (Jan 2026)**	**Nameplate Capacity (tpa Ni)**	**Feed Type**	**Product**	**First Metal**
Huayou – Huafei (IMIP)	Indonesia	Operating	60,000	Limonite	MHP	2023

CNGR – Ruiqing (IMIP)	Indonesia	Operating	60,000	Limonite	MHP	2023
Lygend – QMB (IWIP)	Indonesia	Operating	55,000	Limonite	MHP	2022
GEM – Conch (Obi Island)	Indonesia	Operating	55,000	Limonite	MHP	2024
Huayou – Brunp (Weda Bay)	Indonesia	Operating	120,000	Limonite	MHP	2024–2025
Tsingshan – Rongbay (Sulawesi)	Indonesia	Ramping	50,000	Limonite	MHP	2025
PT Vale Indonesia – Pomalaa (with Huayou)	Indonesia	Late construction	60,000–120,000	Limonite	MHP	2026
Ravensthorpe (First Quantum) – restart	Australia	Operating	~30,000	Limonite	MHP	2024

7.6. Energy and Reagent Consumption Benchmarks (2025–2026)
Modern HPAL operations have achieved significant reductions in reagent and energy intensity compared with earlier generations. Representative consumption figures are shown in the table 9. New projects increasingly target <6 t CO_2e/t Ni through natural gas and/or renewable power integration (Fortune Asia, 2025).

Table 9: Modern HPAL Comparison for reagents and energy intensities

Parameter	**Unit**	**Best-in-Class (2025–2026)**	**Typical 1990s–early 2000s**
Sulfuric acid	kg/t dry ore	250–280	400–600
Electricity	kWh/t Ni	6,500–8,000	12,000–15,000
Steam (from acid plant)	GJ/t Ni	35–40	60–80
CO_2e Scope 1+2 emissions	t CO_2e/t Ni	12–16 (coal) → 4–6 (gas/renewables)	25–35

7.7. Waste Management Evolution (2025–2026)
Early HPAL plants frequently used wet tailings dams or deep-sea tailings placement (DSTP), approaches that have been associated with environmental incidents. Current Indonesian regulatory and industry standards mandate residue neutralisation with limestone to produce gypsum + jarosite/hematite, followed by thickening, filtration to ≥55–60% solids, and dry stacking of the filtered cake. Pilot programs are also investigating residue valorisation opportunities, including iron recovery, geopolymer brick production, and scandium/rare-earth extraction (The Assay, 2022; TAKRAF, 2026).

7.8. Economics (2025–2026)
Despite periodic volatility in sulfur and energy prices, HPAL remains the lowest-cost route for new Class-1 nickel production when nickel prices exceed approximately US$16,000/t. Typical cost metrics for Indonesian projects are presented below (Whittington and Muir,2000, Fortune Asia 2025).

Table 10: Class-1 Nickel Production plant's economics

Item	**US$/t Ni in MHP (Indonesia, 2025–2026)**
Cash cost (C1)	7,800–11,000
All-in sustaining cost (AISC)	9,500–11,500
CapEx intensity	28,000–35,000 per annual tonne Ni
Payback period (at US$20,000/t Ni)	3.5–4.5 years

7.9. Future Directions (2026–2030)
Research and industrial development efforts are pursuing four principal trajectories to further enhance the sustainability, cost competitiveness, and resource efficiency of HPAL technology.

First, alternative leaching media ("HPAL 2.0") utilising nitric or hydrochloric acid are under active investigation to reduce residue volumes, lower reagent costs, and enable processing of more diverse laterite profiles, including higher-magnesium saprolite fractions (McDonald & Whittington, 2008).

Second, direct hydrogen reduction of mixed hydroxide precipitate (MHP) to produce battery-grade nickel products is being developed as a lower-energy, lower-emission alternative to conventional electrowinning or crystallisation routes, with strong interest in green hydrogen integration (Wood Mackenzie, 2023).

Third, incorporation of carbon capture, utilisation, and storage (CCUS) technologies, together with expanded use of renewable or natural gas power, aims to substantially reduce the carbon footprint of HPAL operations in order to meet the increasingly stringent requirements of global battery supply chains (The Assay, 2022).

Finally, hybrid flowsheets that combine HPAL of limonite with atmospheric leaching of saprolite enable fuller utilisation of the entire laterite orebody. In these systems, excess acid from the HPAL circuit is neutralised by reactive saprolite under atmospheric conditions, increasing overall nickel recovery and reducing net acid consumption (McDonald & Whittington, 2008).

8. NCMM IMPLEMENTATION, RECYCLING, AND DEEP OCEAN MISSION INTEGRATION

8.1 NCMM Pillars and Ni–Co Focus

The NCMM, launched with a ₹34,300 crore outlay for FY 2024–25 to 2030–31, is India's central platform for critical minerals, including Ni and Co, and is structured around domestic exploration, overseas acquisition, processing and technology, recycling and circularity, and human capital/finance (Ministry of Mines, 2025b; Press Information Bureau, 2025). NCMM targets 1,200 domestic exploration projects, 50 overseas mining assets, five critical mineral processing parks, two HPAL pilots (~50 kt/year Ni capacity), and 270 kt/year recycling capacity producing ~40 kt of critical metals annually by 2030–31 (Ministry of Mines, 2025b; NIOT, 2025).

8.2 Recycling and Circular Ni–Co Supply

Industrial experience shows advanced battery recycling can recover approximately 90–95% of cobalt and nickel and ~90% of lithium, enabling closed-loop supply chains and reducing primary mining dependence (Battery Council International, 2025; Ellen MacArthur Foundation, 2024). International operators such as Umicore and Redwood Materials demonstrate commercial viability at tens of thousands of tonnes of feed per year, while Indian firms like Attero and Lohum are piloting hydrometallurgical routes with 90–95% Co and Ni recovery (INKWOOD Research, 2025).

Table 8: Indicative Cobalt Recycling Performance.

Operator	Process type	Co recovery (%)	Stage
Umicore	Pyrometallurgy + hydrometallurgy	≈95	Industrial, EU
Redwood	Reductive calcination + hydromet	≈95	Industrial, USA
Attero/Lohum	Hydrometallurgy (India)	90–95	Pilot–early commercial

8.3 Integrating Deep Ocean Mission Seafloor Data with Onshore Exploration

The Deep Ocean Mission, implemented by NIOT, has delineated substantial polymetallic nodule resources in India's Central Indian Ocean Basin contract area containing Ni, Co, Cu, and Mn at grades comparable to or better than many low-grade terrestrial deposits (NIOT, 2024, 2025). Although commercial extraction remains at pilot or pre-commercial stages, these offshore resources represent a significant long-term strategic option for Ni and Co supply (The Metals Company, 2024; NIOT, 2025).

To build a coherent national Ni–Co resource strategy, onshore datasets from GSI (Sukinda and other Ni–Co belts) and offshore datasets from NIOT (nodule abundance, grades, bathymetry, environmental baselines) should be integrated into a unified geodatabase using harmonised coordinate systems and metadata (GSI, 2024; NIOT, 2025). Applying a common resource-classification framework (e.g., UNFC; JORC-compatible categories) to both laterites and nodules allows consistent assessment of resource potential, development timelines, costs, and ESG risks (NITI Aayog, 2024; Ministry of Mines, 2025b).

With this combined database, India can construct alternative Ni–Co supply scenarios to mid-century comparing onshore-dominant pathways (laterites plus recycling) with mixed onshore–offshore pathways where nodules provide a steady Ni–Co baseline; these scenarios should factor HPAL and nodule-processing capex/opex, nodule-collector and environmental-management costs, and recycling scale-up (IEEFA, 2025; NIOT, 2025). This analysis can inform NCMM decisions on exploration allocation, processing-park locations, and international collaborations.

9. INDIA'S STRATEGIC PATHWAYS AND IMPLICATIONS FOR INDIA’S NI–CO SELF-RELIANCE: CHALLENGES AND PATHWAYS IN THE ENERGY TRANSITION

Nickel and cobalt serve as foundational metals in India's accelerating clean energy transition, underpinning stainless steel production for infrastructure, high-nickel lithium-ion battery cathodes (NMC and NCA) for electric vehicles (EVs) and energy storage, and various industrial alloys. As of January 02, 2026, India maintains near-total import dependency for both metals despite substantial domestic resource potential. Nickel resources stand at approximately 189 million tonnes, primarily laterite deposits concentrated in Odisha (with significant occurrences in Jharkhand and scattered deposits elsewhere), while cobalt resources are estimated at 44.9 million tonnes of ore, largely associated with nickel and copper in similar geological settings (USGS, 2025; IEEFA, 2025a). However, economically viable reserves remain limited, and active mining production is negligible: nickel output hovers at ~7.5 kilotonnes per annum (ktpa) from limited operations (primarily Vedanta), and cobalt primary production is effectively zero, with no dedicated mining leases operational for either metal (Ministry of Mines, 2025a).

Consumption patterns reveal the scale of the challenge. Nickel demand, currently around 85 kt in 2025, is dominated by stainless steel (~70%) with a growing battery segment (~15–20%), projected to reach 170 kt by 2030 and potentially exceed 300 kt by 2040, driven by EV targets (6–7 million units by 2030 under NEMMP/FAME-III) and infrastructure growth (IEEFA, 2025b). Cobalt demand, estimated at 10–15 kt in 2025, is increasingly battery-centric (projected 60–70% share by 2030) and could double or triple in the near term. This demand surge creates substantial supply gaps, with India importing 100% of its requirements for both metals—primarily nickel from Indonesia (50%) and refined products from China, and cobalt intermediates from China (which dominates global refining) alongside secondary suppliers like Norway and Finland (IEEFA, 2025a; Ministry of Mines, 2025b). The concentration exposes the country to price volatility, geopolitical risks, and supply chain disruptions, potentially costing billions annually and jeopardizing net-zero goals by 2070.

India's strategic response centers on the National Critical Minerals Mission (NCMM), approved in January 2025 with a total outlay of ₹34,300 crore (₹16,300 crore government funding plus ₹18,000 crore from public sector undertakings [PSUs] and private investment) over seven years (FY 2024–25 to FY 2030–31). The mission prioritizes nickel and cobalt alongside lithium, rare earth elements, and others, encompassing accelerated domestic exploration, overseas asset acquisition, processing infrastructure, recycling scale-up, and capacity building (Press Information Bureau, 2025a). The Geological Survey of India (GSI) leads exploration, with hundreds of projects targeting nickel-rich laterites in Odisha and associated cobalt deposits, plus offshore polymetallic nodules rich in cobalt, nickel, and manganese (Press Information Bureau, 2025b). Regulatory reforms under the Mines and Minerals (Development and Regulation) Act (MMDR) amendments enable central auctions of critical mineral blocks (24 minerals including nickel and cobalt in Part-D), with fast-track clearances and incentives for private participation (Ministry of Mines, 2025c).

Overseas acquisition forms a cornerstone of the strategy through Khanij Bidesh India Ltd (KABIL), the joint venture among NALCO (40%), Hindustan Copper (30%), and Mineral Exploration Corporation Ltd (MECL) (30%). KABIL actively pursues lithium, cobalt, and nickel assets, with ongoing due diligence and partnerships in Australia (MoU since 2022), Argentina (lithium-nickel off-take agreements), Chile, and exploratory engagements in Zambia's copper-cobalt belt. These efforts are reinforced by multilateral frameworks such as the Minerals Security Partnership (MSP) and Quadrilateral Security Dialogue (Quad), promoting diversified, ethical sourcing and strategic stockpiling (60–180 days of supply resilience) (Press Information Bureau, 2025c; Observer Research Foundation, 2025).

Recycling offers a high-impact pathway to secondary supply. The NCMM targets 270 ktpa recycling capacity by 2030–31, supported by a ₹1,500 crore incentive scheme for recovering critical minerals from e-waste, battery scrap, and end-of-life products. Updated Battery Waste Management Rules (2025) enforce Extended Producer Responsibility (EPR) with 90%+ recovery targets, while customs exemptions on waste/scrap reduce costs. Leading recyclers (Attero, Lohum, Recyclekaro) achieve 90–95% recovery rates for nickel and cobalt via hydrometallurgy, positioning the sector to potentially meet 15–30% of demand by 2030 (NITI Aayog, 2023; IEEFA, 2025b).

Downstream processing is advancing through five planned Critical Mineral Processing Parks (e.g., in Odisha and Gujarat), where high-pressure acid leaching (HPAL) and solvent extraction technologies will produce battery-grade nickel sulfate and cobalt sulfate. Centres of Excellence (launched April 2025) drive R&D into low-cobalt alternatives (e.g., LFP/LMFP cathodes) and efficient recovery, complemented by Production-Linked Incentive (PLI) schemes for Advanced Chemistry Cells (PLI-ACC) that support precursor manufacturing (Press Information Bureau, 2025a).

Challenges remain formidable. Long project gestation (5–10 years for mining), environmental and social concerns in tribal areas, limited refining capacity, and heavy reliance on concentrated global sources (China for refining, DRC for cobalt) hinder progress. Informal waste collection and ESG issues in overseas sourcing add complexity (Observer Research Foundation, 2025; IEEFA, 2025a). Overcoming these requires accelerated NCMM implementation, increased private equity in auctions, robust multilateral partnerships, and continued policy incentives for recycling and innovation.

In summary, India's nickel and cobalt position highlights a paradox of significant resource potential juxtaposed against near-total import dependence. The NCMM, KABIL-led acquisitions, recycling incentives, and processing infrastructure provide a comprehensive roadmap toward 30–50% self-reliance by 2035. Successful execution will be essential to secure supply chains, support EV-led growth, and advance India's net-zero objectives by 2070.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

India's pursuit of nickel and cobalt self-reliance is imperative amid escalating demand from the EV sector and clean energy transition, projected to reach 170 kt for nickel and 20–30 kt for cobalt by 2030. Despite abundant lateritic resources (189 Mt nickel, 44.9 Mt cobalt-bearing ore) and offshore polymetallic nodules, current production is minimal, leading to 100% import dependency and exposure to global supply risks dominated by Indonesia, DRC, and China. The NCMM, with its ₹34,300 crore framework, integrates exploration, overseas acquisitions via KABIL, HPAL-based processing, and recycling to target 30–50% self-sufficiency by 2035. Geometallurgical advancements in HPAL, hybrid leaching, and Deep Ocean Mission integration offer promising pathways, but challenges like long lead times, environmental concerns, and geopolitical vulnerabilities persist. Overall, strategic execution could transform India's critical mineral landscape, enhancing energy security and supporting net-zero goals by 2070.

10.2 Recommendations

1. **Accelerate Domestic Exploration and Mapping**: Prioritize 3D geological modelling in Sukinda and Jharkhand, allocating additional funds for AI-driven resource assessments to fast-track reserve delineation within 2–3 years.
2. **Enhance HPAL and Recycling Infrastructure**: Establish pilot HPAL plants in Odisha by 2027 and scale recycling to 270 ktpa, with incentives for 95%+ recovery rates and EPR enforcement to cover 20–30% of demand.

3. **Integrate Onshore-Offshore Data**: Develop a unified geodatabase for GSI and NIOT datasets by 2027, enabling scenario modelling for mixed supply pathways and informing NCMM allocations.
4. **Strengthen International Partnerships**: Expand KABIL's acquisitions in Australia and Africa, leveraging MSP and Quad for ethical sourcing, while building 180-day strategic stockpiles for nickel and cobalt.
5. **Address Challenges Proactively**: Implement ESG frameworks for tribal areas, reduce project gestation through regulatory reforms, and invest in R&D for low-cobalt batteries to mitigate global concentration risks.

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