Strategic Vulnerability Assessment of India’s Critical Minerals: Import Dependence, Trade Risks, and Policy Implications (2017–2024)

Executive Summary

This report evaluates India’s trade dynamics regarding three pivotal critical minerals—Copper, Lithium, and Graphite—essential for the nation’s energy transition and industrial decarbonization. Analyzing EXIM data from 2017 to 2024, the study quantifies the extent of import dependence, assesses supply chain vulnerabilities, and validates the strategic necessity of the National Critical Minerals Mission (NCMM).

Key findings reveal that India’s vulnerability is structural rather than transient. Lithium and Graphite exhibit near-total import reliance (Import Dependency Ratio $\approx$ 1) with negligible export capacity. While Copper demonstrates a comparatively lower risk profile, its dependency is rapidly intensifying. Statistical analysis (ANOVA) confirms that these vulnerabilities predated global disruptions such as the COVID-19 pandemic, indicating deep-seated market failures in domestic capacity generation. Furthermore, the analysis highlights a distinct "risk hierarchy": Graphite presents the highest geopolitical risk due to extreme partner concentration (China), Lithium faces high price-volatility risk, and Copper faces transitional supply deficits. The worsening trade balance across all three minerals underscores a growing macroeconomic challenge, necessitating immediate, differentiated policy interventions involving overseas asset acquisition, diversification, and enhanced recycling frameworks.

Methodology and Data Analysis

1. Introduction

1.1 Context and Rationale

As India accelerates its commitment to renewable energy targets and electric vehicle (EV) adoption, the security of critical mineral supply chains has emerged as a paramount strategic concern. Copper, Lithium, and Graphite act as the fundamental building blocks for EV batteries, energy storage systems (ESS), and power transmission infrastructure. However, the geological scarcity of these minerals within Indian territory creates a significant reliance on global markets.

1.2 Problem Statement

Despite the strategic urgency, there is limited clarity on the specific nature of India's dependence. Is the vulnerability driven by volume shortages, price volatility, or geopolitical concentration? Furthermore, to what extent are these risks structural versus cyclical? This report addresses these questions by analyzing trade patterns to determine the severity of India's external constraints.

1.3 Objectives

The primary objectives of this analysis are to:

- Quantify the magnitude and trajectory of import dependence for Copper, Lithium, and Graphite.
- Assess the economic and strategic risks arising from trade imbalances and partner concentration.
- Validate the necessity of state-led interventions (NCMM) through statistical evidence of market limitations.

2. Data and Methodology

This study utilizes India's Export-Import (EXIM) data spanning the fiscal years 2017 through 2024. The analysis employs a multi-dimensional framework to assess vulnerability, utilizing the following metrics:

- **Import Dependency Ratio (IDR):** To measure the share of domestic consumption met through imports.
- **Net Import Ratio:** To evaluate the trade balance relative to total trade volume.
- **Herfindahl-Hirschman Index (HHI):** To quantify market concentration and partner diversity.
- **Statistical Validation (ANOVA):** To test for structural breaks (Pre/Post-2020) and significance in import intensities across mineral categories.

3. Key Findings and Analysis

3.1 Magnitude of Dependence: A Hierarchy of Vulnerability

The analysis establishes that import dependence is not uniform across minerals but follows a distinct hierarchy.

- **Graphite and Lithium (High Criticality):** Both minerals exhibit an Import Dependency Ratio consistently hovering near 1.0 (100%) throughout the study period. Exports are negligible, confirming a near-total reliance on foreign inputs for domestic consumption.
- **Copper (Transitional Vulnerability):** Copper initially displayed a lower dependency ratio (~0.63 in 2017) due to partial domestic refining capacity. However, this has deteriorated significantly, rising to >0.90 by 2024. This trajectory signals that domestic capacity is

failing to keep pace with the demand surge from electrification.

3.2 Structural vs. Transient Vulnerability (Temporal Analysis)

A critical finding of this report is the nature of the dependence. Analysis of Variance (ANOVA) comparing pre-2020 and post-2020 import values reveals no statistically significant structural break ($p > 0.05$).

- **Interpretation:** India's import dependence was not triggered solely by post-pandemic supply shocks or the recent EV boom. Rather, the vulnerability is structural and existed well before 2020. This indicates a long-standing failure of market mechanisms to incentivize domestic exploration or substitution, thereby justifying the state-led intervention envisioned by the NCMM.

3.3 Price Risk vs Structural Demand (Value-Volume Dynamics)

The relationship between import value and volume growth offers specific insights into the nature of risk for each mineral:

- **Lithium (Price Risk):** Data shows periods where import values spiked sharply despite modest volume growth. This divergence indicates that India is a "price taker" in the global Lithium market, highly exposed to external commodity price shocks and exchange rate volatility.
- **Graphite (Structural Lock-in):** Both value and volume exhibit sustained upward trends. This correlation implies that rising imports are driven by fundamental structural demand from the battery sector, rather than temporary price effects.

4. Risk and Impact Assessment

4.1 Supply Chain and Geopolitical Risk

The analysis of partner concentration highlights asymmetric risks:

- **Graphite:** Shows extreme concentration, with China dominating as the primary supplier. The high HHI values for Graphite indicate a "single-point failure" risk, exposing India's battery ecosystem to potential export restrictions or diplomatic friction.
- **Lithium:** Exhibits emerging concentration (Argentina, Belgium, China, Chile). While slightly more diversified than Graphite, the supply chain remains narrow, posing logistical and political risks.
- **Copper:** Remains the most resilient, with a diversified basket of partners (Japan, Chile, Indonesia), mitigating immediate geopolitical coercion risks.

4.2 Economic Vulnerability and Trade Deficits

The trade balance analysis reveals a worsening deficit across all three minerals, particularly post-2021.

- **Forex Drain:** The persistent net-importer status results in significant foreign exchange outflows. As the energy transition scales, this "green inflation" could strain India's Current

Account Deficit (CAD).
- **Cost Transmission:** High import costs for Lithium and Graphite are directly passed through to downstream industries, potentially rendering Indian-manufactured EVs and energy storage systems globally uncompetitive without subsidies.

4.3 Energy Transition Risk

ANOVA results confirm statistically significant differences in import intensity ($p \ll 0.01$), proving that Lithium and Graphite are structurally more import-intensive than traditional industrial metals. Consequently, India's energy transition is externally constrained; the pace of domestic decarbonization is dictated by the availability and pricing of foreign mineral supplies.

5. Discussion

The findings of this report strongly refute the notion that India's critical mineral challenges are temporary market fluctuations. The data characterizes the situation as a **Market Failure** in self-correction. Despite rising prices and demand, there has been no natural diversification of partners for Graphite, nor has there been significant domestic import substitution.

The worsening trade balance—specifically the sharp deterioration in 2022–2024—coincides with global energy transition acceleration. This suggests that without intervention, India risks trading energy security (dependence on oil) for mineral security (dependence on battery minerals), merely shifting the geopolitical point of vulnerability from the Middle East to mineral-rich nations and processing hubs like China.

6. Strategic Recommendations

Based on the distinct risk profiles identified, the following policy interventions are recommended:

6.1 For Graphite: Urgent Diversification & Substitution

Given the extreme concentration risk and structural dependence, policy must prioritize:

- **Diversification:** Aggressive diplomatic engagement with non-traditional Graphite producers (e.g., Africa, Brazil) to reduce reliance on the dominant supplier.
- **Synthetic Alternatives:** R&D incentives for the development and scaling of synthetic graphite production to bypass geological constraints.

6.2 For Lithium: Asset Acquisition & Long-Term Contracting

To mitigate the high price volatility and supply insecurity:

- **Overseas Assets:** KABIL (Khanij Bidesh India Ltd) should prioritize equity stakes in Lithium assets in the "Lithium Triangle" and Australia to secure physical offtake rights.
- **Hedging Mechanisms:** Encouraging long-term supply contracts with price-smoothing

mechanisms to insulate downstream manufacturers from spot market volatility.

6.3 For Copper: Circular Economy & Refining

With rising dependence but a diversified supply base:

- **Scrap Policy:** Enhance the domestic recycling ecosystem to recover Copper from e-waste and industrial scrap, slowing the growth of the Import Dependency Ratio.
- **Refining Capacity:** Expand domestic smelting capabilities to allow for the import of lower-cost concentrates rather than finished refined copper.

Structural Rigidity and Strategic Vulnerability in India’s Critical Mineral Supply Chain

A Trend Analysis of Copper, Lithium, and Graphite

1. Executive Summary

This report analyzes the structural vulnerabilities inherent in India’s supply chain for three critical minerals: Copper, Lithium, and Graphite. As India accelerates its transition to clean energy, reliance on global markets has exposed the economy to specific upstream and midstream risks.

The analysis reveals that **Copper** supply is constrained by geological deterioration and extreme inelasticity (long lead times), making price volatility a structural norm rather than a cyclical event. Conversely, **Lithium and Graphite** vulnerabilities are located in the midstream; despite domestic reserves of graphite, India suffers from a "value-addition gap," remaining dependent on Chinese processing. Furthermore, the report identifies that global trade is increasingly governed by opaque contracting structures (offtake agreements) and geopolitical fragmentation (export bans), rather than open spot markets.

The report concludes that India’s current import strategy faces significant threats from "allied-sourcing" blocs and rising ESG-related supply shocks. Strategic resilience will require a pivot from simple resource acquisition to deep investments in domestic refining capacity and long-term sovereign contracting.

2. Introduction

2.1 Context
The global energy transition has precipitated a paradigm shift in commodity markets, transforming niche minerals into critical macroeconomic assets. For India, ensuring a steady supply of Copper, Lithium, and Graphite is prerequisite to achieving manufacturing targets in electric mobility, renewable energy storage, and infrastructure development.
2.2 Problem Statement
Current EXIM (Export-Import) data trends suggest a misalignment between India’s import strategies and the shifting realities of global supply chains. There is a need to distinguish between mere resource availability and actual "accessible" supply, which is increasingly constrained by processing monopolies, geopolitical shielding, and declining ore quality.
2.3 Objectives

- To analyze the specific structural constraints affecting Copper, Lithium, and Graphite.
- To evaluate the impact of financial contracting and export controls on material availability.
- To assess the disconnect between India's domestic mining regulations and global ESG standards.

3. Data and Methodology

This analysis utilizes a qualitative and quantitative assessment of global supply chain trends, geological data, and trade policy frameworks. Key indicators analyzed include:

- **Upstream Metrics:** Mine project lead times, ore grade degradation rates, and production concentration.
- **Midstream Metrics:** Refining capacity distribution (specifically China's market share) and import composition (raw ore vs. processed derivatives).
- **Market Structure:** Prevalence of offtake agreements, joint ventures, and vertical integration.
- **Risk Factors:** Analysis of geopolitical export bans, ESG-related disruptions, and regulatory divergences.

4. Key Findings and Analysis

The analysis categorizes the commodities into two distinct risk profiles: Upstream-Constrained (Copper) and Midstream-Constrained (Lithium/Graphite).

4.1 Copper: Geological Scarcity and Inelasticity

The analysis indicates that Copper faces a crisis of upstream quality and timeline rigidity. With average project lead times stretching to approximately 17 years, supply is highly inelastic; immediate demand signals cannot trigger rapid production increases. Furthermore, a 30% decline in ore grades in major producers like Chile signifies a permanent structural deterioration in supply efficiency.

- **Implication for India:** Rising import volumes will likely coincide with rising unit costs due to declining global efficiency. Reliance on Hindustan Copper Limited (HCL) without significant overseas asset acquisition leaves India exposed to these global inefficiencies.

4.2 Lithium: The Processing Choke Point

Unlike Copper, Lithium's scarcity is not geological but industrial. The supply chain is dominated by processing capacity, where China controls approximately 60% of refining. India's vulnerability is characterized by a dependency on chemical conversion (Carbonate/Hydroxide) rather than raw ore.

- **Implication for India:** Trade security cannot be achieved by securing raw spodumene alone; without domestic refining capabilities, India remains dependent on the Chinese conversion ecosystem.

4.3 Graphite: The Value-Addition Paradox

Graphite presents a unique anomaly where India possesses significant natural reserves yet remains strategically dependent. This "Import Paradox" is driven by a lack of spherical graphite processing capabilities. While China controls 92% of battery-grade graphite, India's imports of processed graphite continue to rise despite domestic mining potential.

- **Implication for India:** The dependency is purely technological. The price premium paid by India reflects value-added barriers, not material scarcity.

5. Risk and Impact Assessment

Beyond commodity-specific trends, the report identifies three macro-structural risks altering the trade landscape.

5.1 Financial Control of Supply (The "Invisible" Market)

Trade data often misrepresents availability because a significant portion of global supply is locked into long-term offtake agreements and streaming contracts. With over 40% of top mine output tied to Joint Ventures or vertical integration by OEMs, the "spot market" is becoming residual.

- **Risk:** India, as a late entrant, faces a market where physical availability is pre-committed. Sudden drops in imports may not reflect demand destruction but rather contractual reallocation to other jurisdictions.

5.2 Geopolitical Fragmentation and Trade Barriers

The rise of "resource nationalism"—manifested through export bans (Indonesia, Zimbabwe) and licensing regimes (China)—has transformed trade flows. Additionally, policies like the US Inflation Reduction Act (IRA) have created "allied-sourcing" blocs.

- **Risk:** These are structural shocks, not market failures. They function as non-tariff barriers that fragment the global market, potentially isolating India if it falls outside specific political trade blocs.

5.3 Global ESG as a Supply Constraint

Environmental, Social, and Governance (ESG) factors have evolved from reputational risks to hard supply constraints. Water stress in South America and social unrest in Africa are physical limiters of production.

- **Risk:** Volatility in EXIM trends is increasingly correlated with ESG events (strikes, permit revocations) rather than traditional demand-supply mechanics.

6. Discussion: The Regulatory Alignment Gap

A critical finding is the divergence between India's domestic regulatory approach and global market expectations. To expedite domestic production, India's mining framework has moved toward streamlining approvals (e.g., exemptions from public hearings). While this improves

short-term speed, it creates a long-term strategic risk.

Global markets are increasingly mandating lifecycle accountability and adherence to standards like Free, Prior, and Informed Consent (FPIC). If India's domestic output does not meet these traceability and social license standards, Indian downstream manufacturers may face non-tariff barriers when exporting finished goods to ESG-sensitive markets (EU, USA). This regulatory misalignment poses a threat where India's "fast-tracked" minerals become non-compliant in the global value chain.

7. Conclusion

The trend analysis confirms that India's critical mineral security is threatened not just by volume, but by the structural complexity of the supply chain.

- **Copper** risks are geological and require geographic diversification.
- **Lithium and Graphite** risks are industrial and require technological upgrading.
- **Trade Access** is restricted by financial interlocking (offtake agreements) rather than open market dynamics.

India is currently navigating a market defined by high inelasticity, processing monopolies, and geopolitical fragmentation. A passive import strategy is no longer viable.

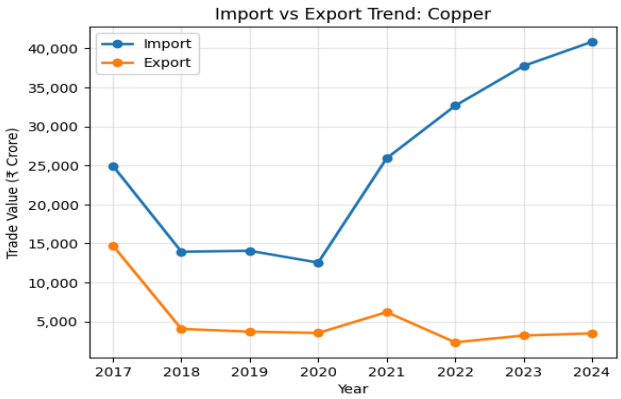
8. Strategic Recommendations

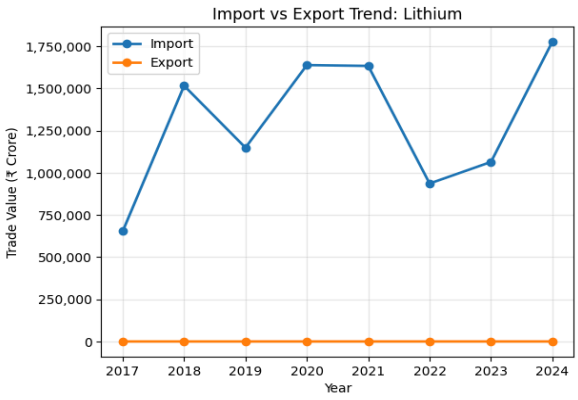
Based on the analytical findings, the following actions are recommended:

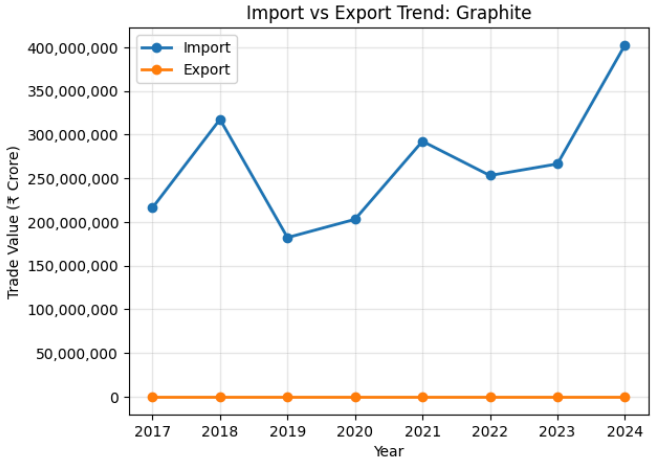
- **Establish Sovereign Midstream Capability:** For Lithium and Graphite, policy incentives must shift from mining to **refining**. Subsidies should target the establishment of chemical conversion and spherical graphite processing facilities to close the value-addition gap.
- **Pursue Asset Equity over Spot Trade:** To counter the risk of offtake lock-ins, Indian PSUs and private entities must aggressively pursue equity stakes in overseas mines to secure physical offtake rights, specifically in Copper and Lithium assets in Africa and South America.
- **Harmonize ESG Standards:** India must align its domestic mining regulations with global best practices (traceability and social license). Relaxing environmental norms for speed creates a "compliance debt" that could penalize future exports.
- **Diversify Import Partners based on Processing:** EXIM analysis must track "value-added" import partners. Reduce dependency on single-source processing hubs (China) by building trade relationships with emerging refining markets (e.g., Australia, Vietnam).

Insights from Trade Data Visualizations

1. Import vs Export Trend (by mineral)







Copper

- Copper imports consistently exceed exports throughout 2017–2024, confirming India as a **structural net importer** of copper.
- Import values rise sharply after 2020, increasing from ~₹12,500 crore (2020) to over **₹40,000 crore by 2024**, indicating accelerating external dependence.
- Exports remain limited and volatile, peaking briefly in 2021 (~₹6,000 crore) but declining

thereafter.

- The widening import–export gap post-2020 highlights **growing trade imbalance and rising supply vulnerability**, despite partial domestic capacity.

Lithium

- Lithium imports dominate trade completely, while exports remain **negligible across all years**, reflecting near-total import reliance.

- Import values increase from ~₹6,500 crore (2017) to approximately **₹17,500 crore by 2024**, with sharp year-to-year volatility.

- The absence of meaningful export activity indicates **no domestic value chain offset**, making lithium imports highly sensitive to global price and supply shocks.

- This pattern underscores lithium as a **critical bottleneck mineral** for India's EV and energy storage ambitions.

Graphite

- Graphite exhibits the **largest absolute import values** among the three minerals, rising from ~₹2.2 lakh crore (2017) to over **₹4.0 lakh crore by 2024**.

- Exports are effectively zero throughout the period, indicating **absolute import dependence**.

- Import growth remains strong even during global disruptions, suggesting **structural demand expansion rather than cyclical trade effects**.

- The sustained dominance of imports signals **long-term strategic vulnerability**, particularly given graphite's importance in battery anodes.

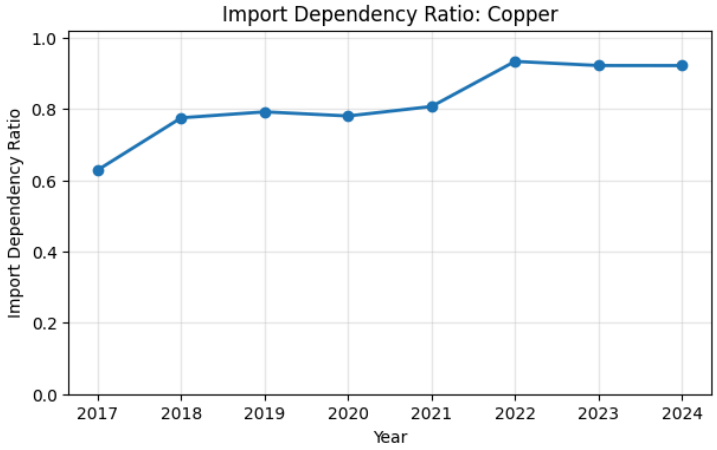
Cross-Mineral Insight

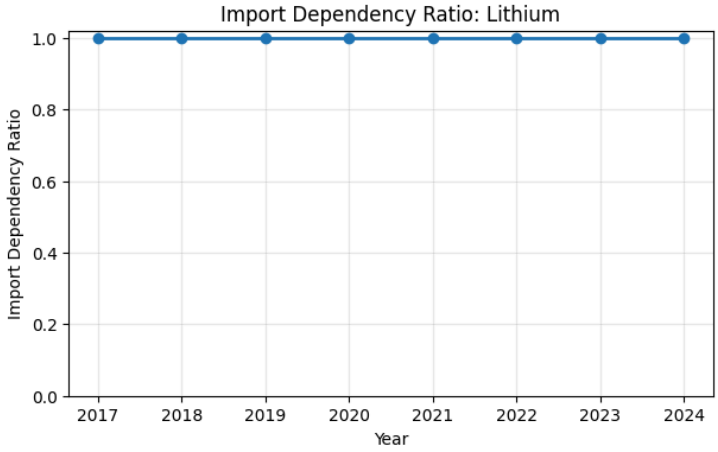
- Across all three minerals, imports overwhelmingly exceed exports, but **the degree of dependence differs**:

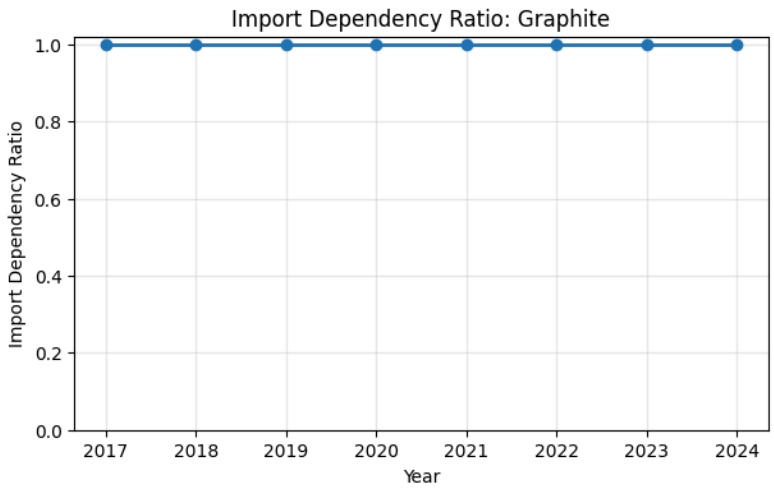
    - Copper shows rising but partially mitigable dependence,

    - Lithium reflects high and volatile dependence,
    - Graphite demonstrates extreme and entrenched import reliance.
- The post-2020 acceleration in import values aligns with the global energy transition, indicating that **India's clean-energy growth is increasingly import-intensive**.

2. Import Dependency Ratio







Copper

- Copper's import dependency ratio rises steadily from **~0.63 in 2017 to above 0.90 by 2022–2024**, indicating a sharp increase in external reliance.
- Despite some domestic production and recycling capacity, imports account for an **increasing share of total copper trade**, suggesting erosion of self-sufficiency.
- The post-2020 acceleration in dependency aligns with rising demand from electrification, grid expansion, and infrastructure growth.
- This trend indicates that copper is transitioning from **manageable dependence to strategic vulnerability** if domestic capacity is not scaled.

Lithium

- Lithium's import dependency ratio remains **at or extremely close to 1 across all years**, reflecting **near-total import dependence**.
- The flat trajectory indicates that India has **no meaningful domestic production or export offset** for lithium.
- This structural dependence existed even before 2020 and persists through the rapid expansion of EV and battery demand.
- As a result, India's lithium supply is **fully exposed to global market dynamics and geopolitical risks**.

Graphite

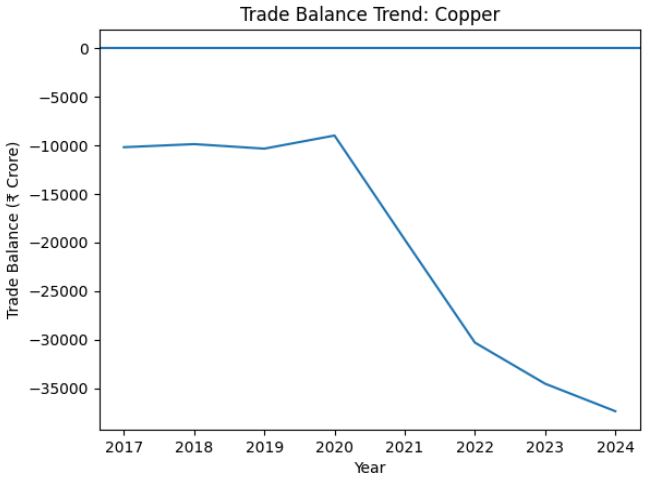
- Graphite also exhibits an import dependency ratio consistently **equal to 1 throughout the study period**, indicating **absolute import reliance**.
- Unlike lithium, this dependence is driven not only by price effects but also by **sustained volume growth**, reflecting structural demand expansion.

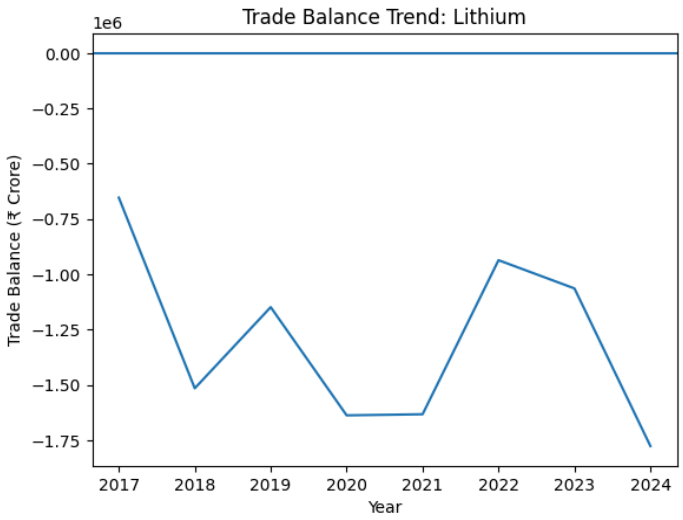
- The lack of any reduction in dependency over time suggests **deep-rooted supply constraints** and limited domestic substitution.
- This positions graphite as the **most structurally vulnerable mineral** among the three.

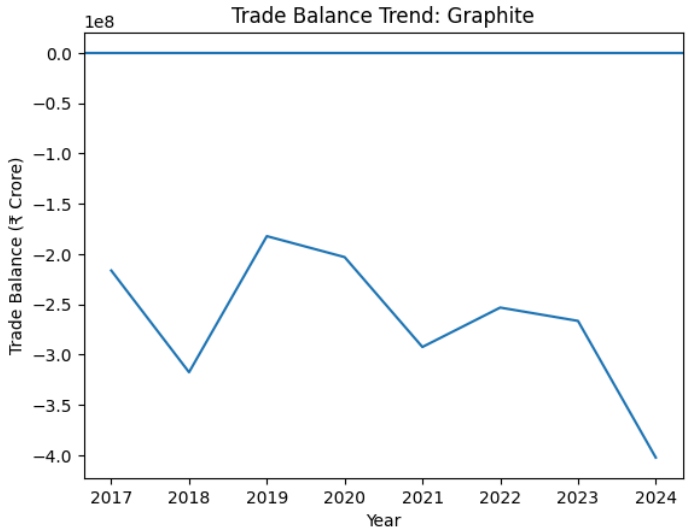
Cross-Mineral Insight

- The import dependency ratio highlights clear heterogeneity across minerals:
    - **Copper** shows rising but potentially reversible dependence,
    - **Lithium and Graphite** exhibit complete and persistent dependence.
- These patterns confirm that India's critical mineral challenge is **not uniform**, necessitating **mineral-specific policy interventions**.
- The results reinforce the urgency of targeted strategies under the National Critical Minerals Mission, particularly for minerals critical to the energy transition.

3. Trade Balance Trend







Copper

- Copper exhibits a **persistent trade deficit** throughout the period, confirming India as a net importer.
- The deficit remains relatively stable between **2017–2020 (≈ –₹9,000 to –₹11,000 crore)**, followed by a **sharp deterioration post-2021**.
- By 2024, the trade deficit widens to **approximately –₹37,000 crore**, reflecting accelerated import growth.
- This worsening balance coincides with rising demand from electrification and infrastructure, indicating **import-led demand growth without matching export capacity**.

Lithium

- Lithium shows a **consistently negative trade balance**, driven by negligible exports and volatile import values.
- The deficit fluctuates but remains large across all years, reaching **around –₹1.7 million crore by 2024**.
- The absence of export recovery suggests **complete dependence on foreign suppliers**, making the trade balance highly sensitive to global lithium prices.
- This volatility highlights lithium as a **price-sensitive strategic mineral**, with direct implications for EV cost structures.

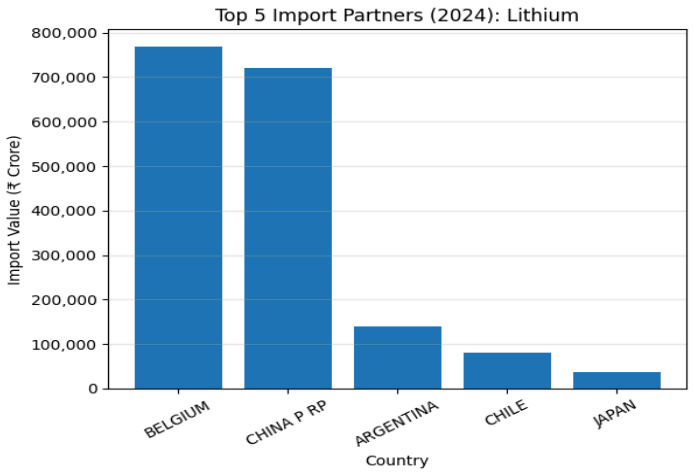
Graphite

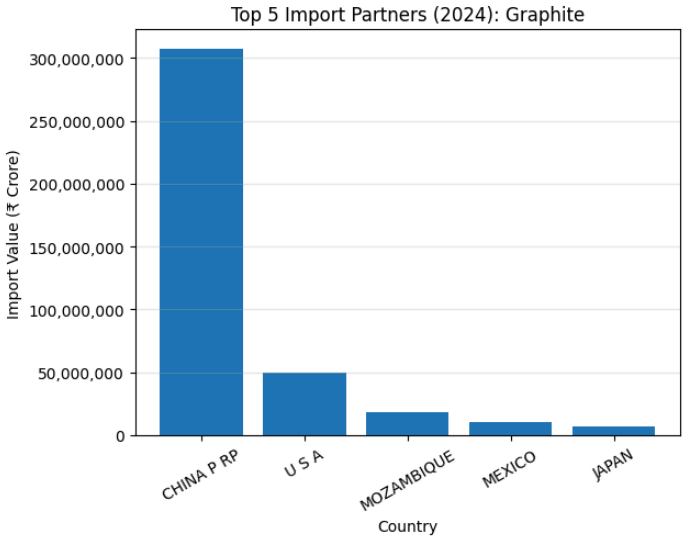
- Graphite records the **largest absolute trade deficits** among the three minerals.
- Deficits worsen over time, deepening from **~–₹2.2 lakh crore (2017)** to **~–₹4.0 lakh crore by 2024**.
- The consistently negative and widening trade balance reflects **structural import dependence rather than cyclical trade effects**.
- The magnitude of the deficit underscores graphite as a **critical macroeconomic and supply-chain vulnerability**.

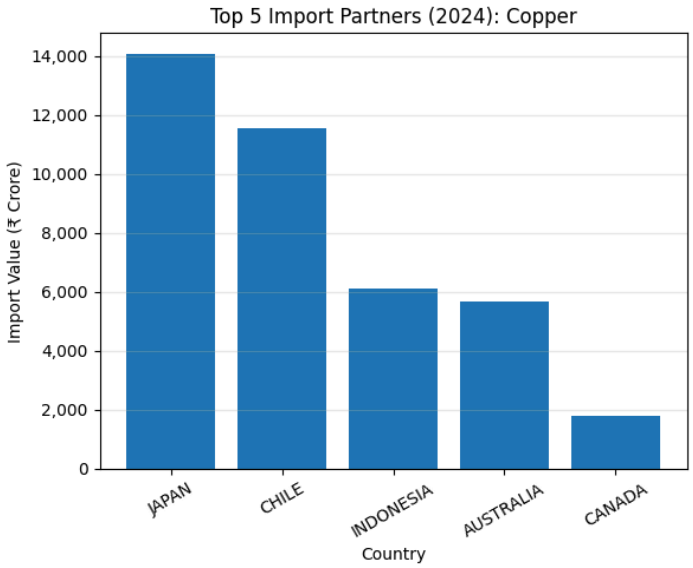
Cross-Mineral Insight

- All three minerals exhibit **persistent and worsening trade deficits**, reinforcing India's import-led engagement with critical minerals.
- Post-2020 trends show a clear acceleration in deficits, aligning with global energy transition pressures.
- The trade balance analysis highlights **foreign exchange exposure and downstream cost pass-through risks**, especially for battery-related minerals.
- These patterns strengthen the case for **domestic capacity creation and strategic sourcing policies** under the National Critical Minerals Mission.

4. Top Import Partners


Top 5 Import Partners (2024): Lithium
Import Value (₹ Crore)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
BELGIUM
CHINA P RP
ARGENTINA
CHILE
JAPAN
Country


Top 5 Import Partners (2024): Graphite
Import Value (₹ Crore)
300,000,000
250,000,000
200,000,000
150,000,000
100,000,000
50,000,000
0
CHINA P RP
U S A
MOZAMBIQUE
MEXICO
JAPAN
Country


Top 5 Import Partners (2024): Copper
Import Value (₹ Crore)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
JAPAN
CHILE
INDONESIA
AUSTRALIA
CANADA
Country

Graphite

- China dominates India's graphite imports in 2024, accounting for **over 70–75% of total import value**, far exceeding all other partners.
- The next largest suppliers (USA, Mozambique, Mexico, Japan) contribute **marginal shares individually**, indicating limited diversification.
- This extreme concentration confirms **structural single-partner dependence**, rather than temporary trade imbalance.
- Such dominance exposes India to **high geopolitical and supply disruption risk**, particularly given China's recent export controls on graphite-related materials.

Lithium

- Lithium imports are concentrated among a **small set of partners**, with **Belgium and China** together accounting for the majority of import value.
- Argentina and Chile contribute secondary shares, while Japan plays a minor role.
- The presence of multiple partners indicates some diversification, but **import values remain heavily skewed toward the top two suppliers**.
- This pattern reflects **emerging concentration risk**, where sourcing flexibility exists but dependence remains high.

Copper

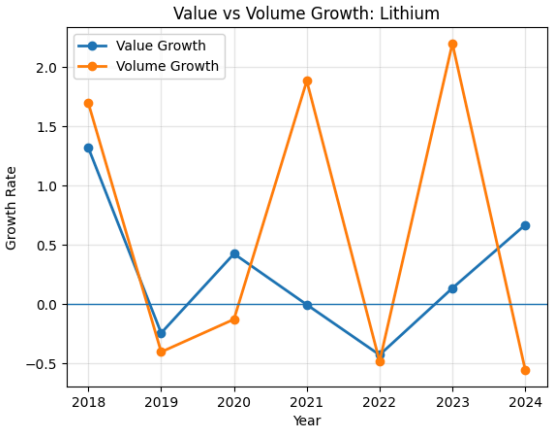
- Copper imports are relatively **more diversified**, with Japan, Chile, Indonesia, Australia, and Canada all contributing meaningful shares.
- No single country overwhelmingly dominates total import value.
- This diversified partner structure reduces immediate geopolitical exposure compared to Lithium and Graphite.
- However, rising absolute import volumes imply that **diversification alone does not eliminate dependence risk**.

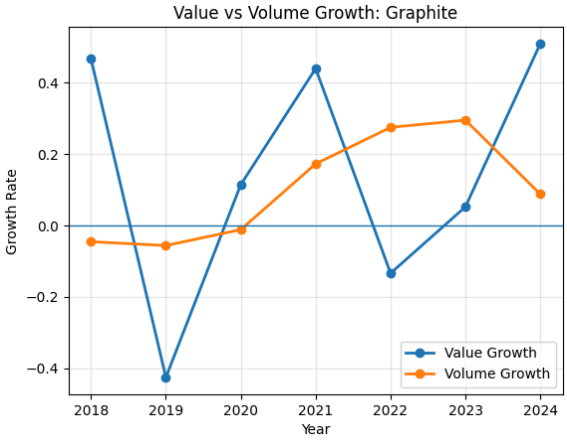
Cross-Mineral Insight

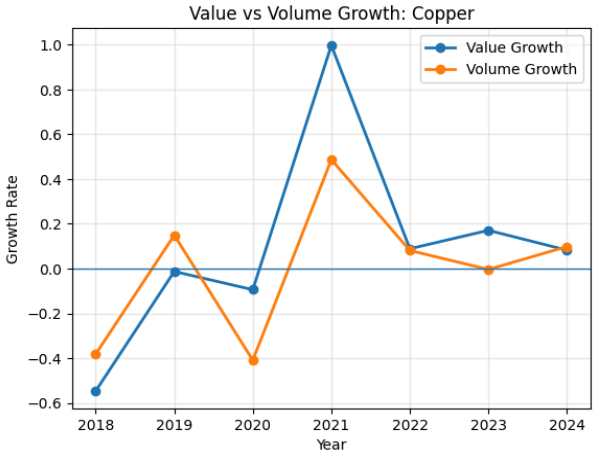
- Partner concentration varies sharply across minerals:
    - **Graphite** → extreme concentration and highest supply-chain risk
    - **Lithium** → high dependence with emerging but incomplete diversification
    - **Copper** → comparatively diversified sourcing
- These differences reinforce the need for **mineral-specific sourcing and diplomatic strategies** under India's critical mineral policy framework.
- Partner concentration analysis complements dependency and trade balance metrics,

together highlighting **where India is most strategically exposed**.

5. Value vs Volume Growth (Price vs Structural Dependence)







Copper

- Copper imports increased sharply after 2020, rising from ~₹12,500 Cr (2020) to over ₹40,000 Cr by 2024, indicating a **structural post-pandemic surge in import reliance**.
- Exports declined significantly after 2017 and remained relatively flat, fluctuating between ~₹2,000–₹4,000 Cr post-2020.
- The widening gap between imports and exports post-2021 highlights a **persistent and worsening trade deficit**, signaling rising external dependence.
- Import growth far outpaces export recovery, suggesting that **domestic demand growth is not matched by domestic processing or export competitiveness**.

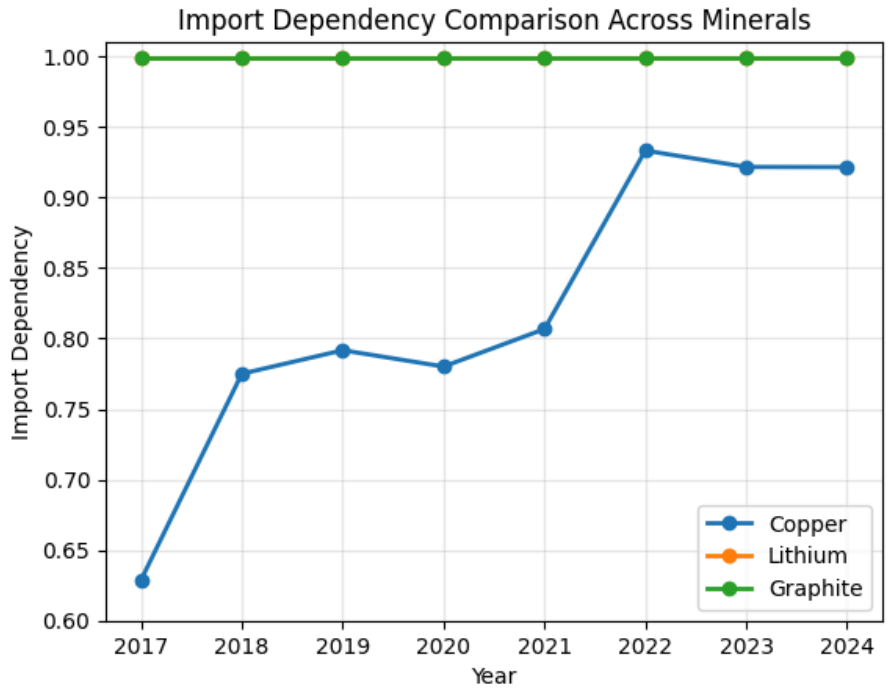
Lithium

- Lithium imports dominate the trade profile entirely, with imports rising from ~₹6.5 lakh Cr (2017) to ~₹17.5 lakh Cr (2024).
- Exports remain **negligible (near zero)** across all years, indicating **near-total import dependence**.
- Import volatility is visible (notably dips in 2019 and 2022), pointing to **price volatility and supply-side shocks** rather than stable sourcing.
- The data reflects lithium's role as a **strategic vulnerability for EV and battery supply chains**, with no offsetting export capability.

Graphite

- Graphite imports are extremely high and rising, crossing ~₹4 lakh Cr by 2024, with a strong post-2021 acceleration.
- Exports remain close to zero throughout the period, similar to lithium but at a much larger absolute scale.
- Import spikes (2018, 2021, 2024) indicate **demand-driven dependence**, likely linked to batteries, electrodes, and industrial use.
- The magnitude and persistence of imports confirm graphite as a **high-risk critical mineral with no export hedge**.

6. Cross Mineral Dependency Comparison



Key Observations

- **Lithium and Graphite exhibit near-absolute import dependence (~100%) across all years**, confirming that India has **no meaningful domestic supply or export offset** for these minerals.

- **Copper shows a steadily rising import dependency**, increasing from ~63% in 2017 to over **92% by 2022**, and remaining above 90% through 2024.

- The sharp increase in copper dependency post-2021 indicates a **structural shift**, not a temporary shock, likely driven by rising demand from power, EV, and infrastructure sectors.

- Unlike copper, lithium and graphite show **no variability** in dependency ratios, highlighting **zero diversification or resilience** in their trade structure.

Comparative Risk Interpretation

- **Lithium & Graphite** represent **extreme vulnerability minerals**:

    - Any supply disruption, export restriction, or geopolitical shock directly translates into domestic risk.

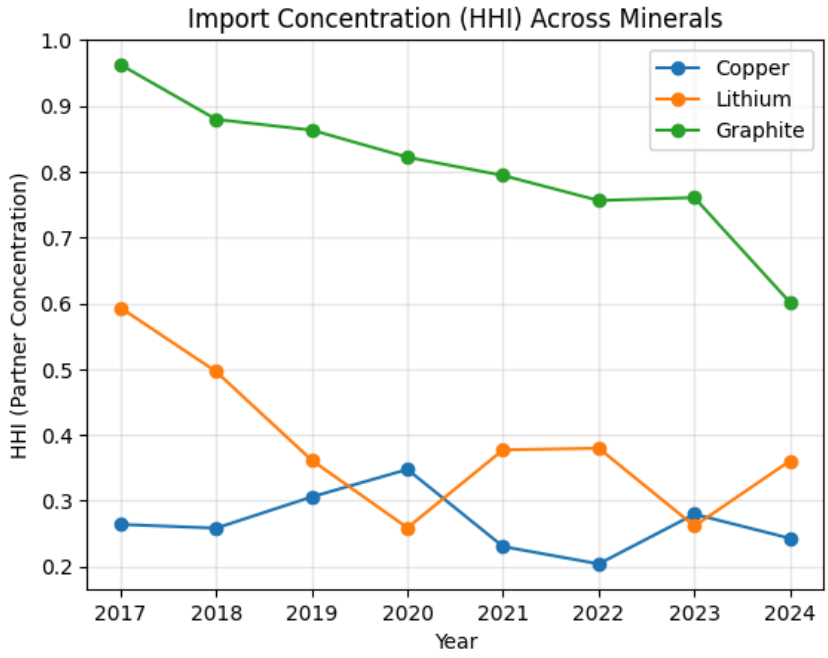
    - No export capacity exists to cushion price or supply shocks.

- **Copper represents an accelerating vulnerability**:
    - While not fully import-dependent, its trajectory shows India is **moving toward high-risk dependence levels**.
    - Rising dependency despite domestic mining presence suggests **downstream processing and refining gaps**.

Strategic & Policy Implications

- This divergence clearly supports the rationale for the **National Critical Minerals Mission (NCMM)**:
    - Lithium and graphite require **urgent diversification, overseas asset acquisition, and recycling strategies**.
    - Copper requires **domestic capacity expansion and value-chain strengthening**, not just import substitution.
- The chart establishes a **prioritisation logic**:
    - **Lithium & Graphite → strategic security risk**
    - **Copper → emerging structural dependence risk**

7. Import Concentrations (Measures partner dependence / supply chain risk)



(HHI closer to 1 ⇒ high dependence on few partners; closer to 0 ⇒ diversified imports)

Graphite

- Graphite shows extremely high import concentration, with **HHI above 0.9 in 2017,** indicating near-monopoly dependence on a single supplier.
- Although **HHI declines gradually to ~0.60 by 2024**, it remains well above safe diversification thresholds, signaling persistent supply chain fragility.
- The slow reduction in concentration suggests incremental diversification, but not enough to offset geopolitical or trade-disruption risk.
- **Given graphite's critical role in batteries and EVs**, this concentration amplifies energy transition vulnerability.

Lithium

- Lithium exhibits moderate-to-high concentration, with **HHI declining from ~0.59 (2017) to ~0.36 (2024).**

- The initial **drop indicates partial diversification of import partners, l**ikely through new trade relationships post-2019.

- However, periodic rebounds in **HHI (2021–2022) show instability in sourcing,** suggesting that diversification is not structurally locked in.

- **Lithium remains exposed to price volatility and supplier-side shocks**, even if concentration risk is lower than graphite.

Copper

- Copper shows the lowest and most stable HHI levels among the three minerals, **mostly between 0.20–0.35.**

- This **indicates a relatively diversified import** base, reducing immediate supply concentration risk.

- However, low concentration does not offset the rising import dependency observed earlier, **implying vulnerability through volume** exposure rather than partner dominance.

Cross-Mineral Risk Comparison

- **Graphite = highest supply chain concentration risk (partner dominance).**

- **Lithium = moderate concentration but unstable diversification.**

- **Copper = diversified partners but rising import volumes, shifting risk from *who* supplies to *how much* is imported.**

Policy-Relevant Insight

- The results reinforce a dual-risk framework:

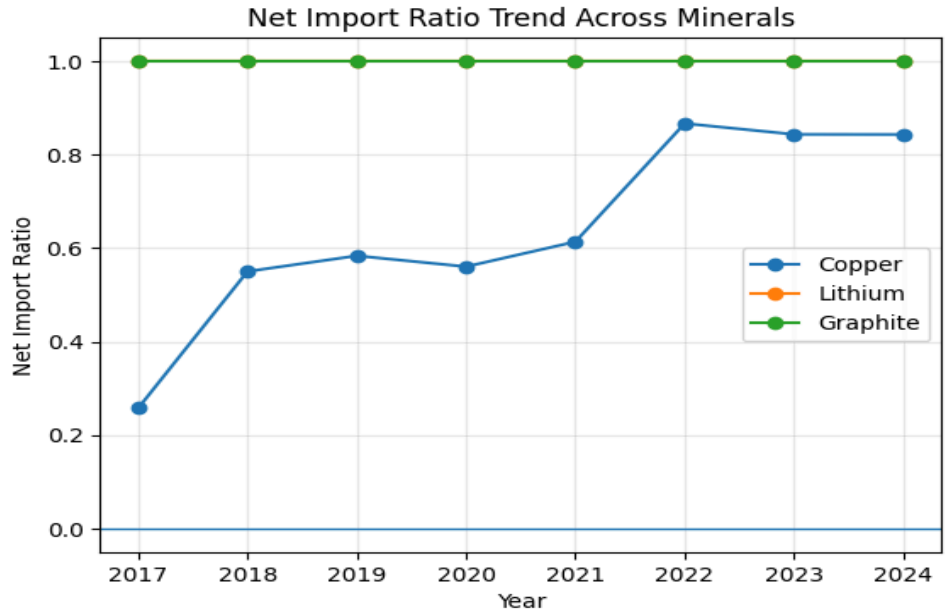
    - Concentration risk (Graphite, Lithium) → diversify partners, overseas mining, strategic reserves.

    - Volume dependence risk (Copper) → domestic processing, recycling, and

substitution.

- This differentiation strengthens the justification for mineral-specific policy instruments under NCMM, rather than a one-size-fits-all approach.

8. Net Import ratio trend



(Net Import Ratio = (Imports − Exports) / Total Trade; values → 1 imply near-total import dependence)

Graphite

- Graphite exhibits a **net import ratio of ~1.0 consistently from 2017–2024**, indicating **almost zero export offset**.

- This confirms **absolute import dependence**, with India functioning purely as a consumption market rather than a value-chain participant.

- Such a profile represents **maximum strategic vulnerability**, as any external supply disruption directly impacts domestic industries.

- The absence of improvement over time suggests **no meaningful progress in domestic value addition or export capability**.

Lithium

- Lithium also shows a **net import ratio ≈ 1.0 across all years**, reinforcing **complete external dependence**.
- Despite fluctuations in import values (seen earlier), exports remain negligible, implying **no downstream processing or re-export activity**.
- This is particularly critical given lithium's role in **EVs, energy storage, and clean-tech**, making India structurally exposed during global demand shocks.
- The trend strongly supports lithium's classification as a **high-priority strategic mineral under NCMM**.

Copper

- Copper shows a **sharp rise in net import ratio** from ~0.26 (2017) to **~0.86 by 2022**, stabilising above **0.84 through 2024**.
- This reflects a **transition from partial self-balancing trade to strong net import dependence** over time.
- Unlike lithium and graphite, copper's vulnerability has **worsened structurally**, not remained static.
- The shift coincides with rising infrastructure, power, and manufacturing demand, indicating **demand-driven dependence**.

Cross-Mineral Comparison

- **Lithium & Graphite**: structurally import-dependent from the outset → *legacy vulnerability*.
- **Copper**: rapidly increasing net import ratio → *emerging vulnerability*.
- This distinction highlights that **policy urgency differs by mineral**, even if all are critical.

Economic & Strategic Implications

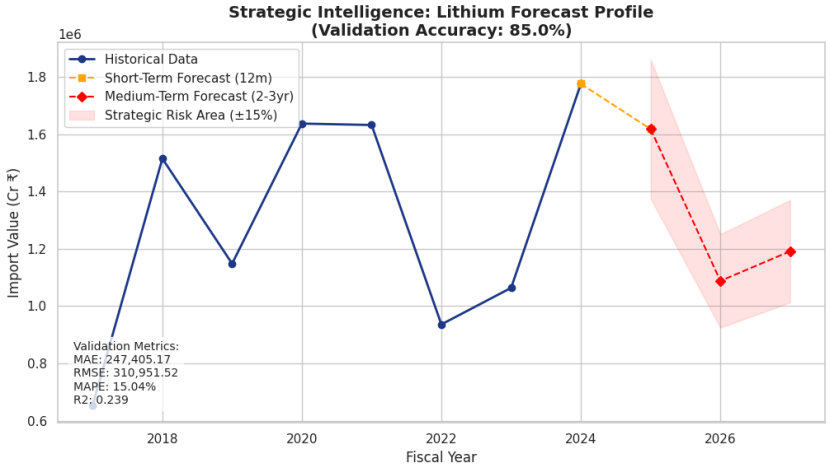
- Persistent net import ratios near 1 imply:
    - **Continuous forex outflow**
    - **Exposure to global price cycles**
    - **Limited strategic leverage in trade negotiations**
- For lithium and graphite, the risk is **binary (supply on/off)**.
- For copper, the risk is **scale-based**, worsening as demand rises.

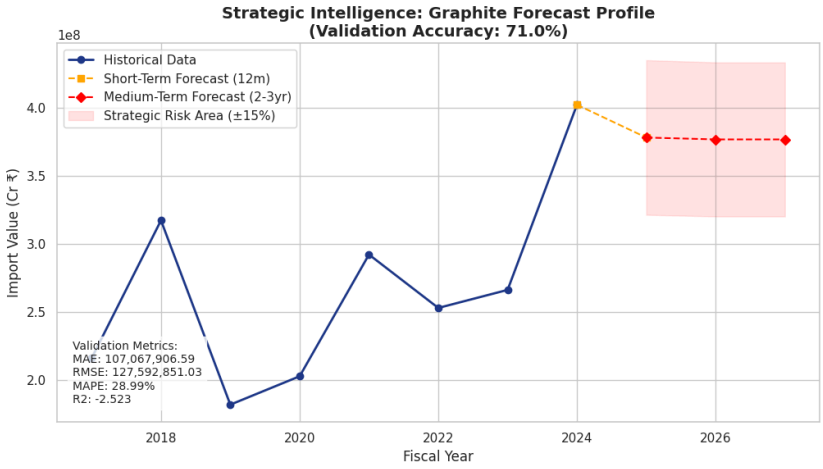
Policy-Relevant Insight

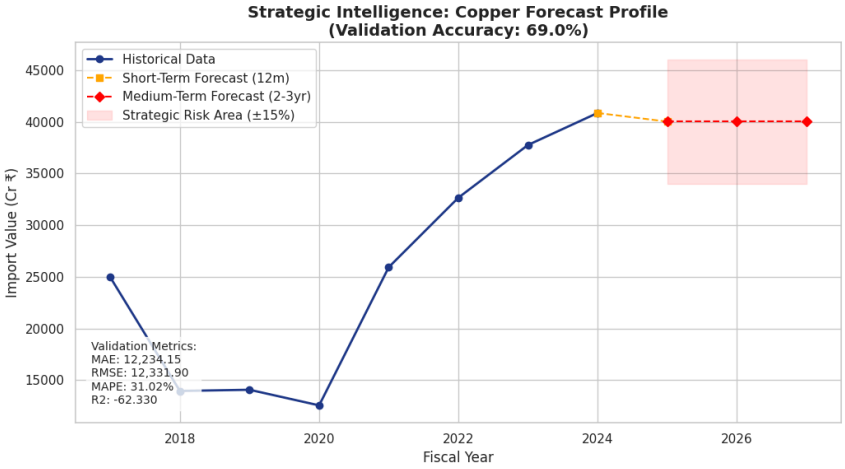
- The chart provides quantitative justification for:
    - **Overseas asset acquisition** (lithium, graphite)
    - **Recycling and circular economy policies** (copper)
    - **Domestic refining and downstream incentives** across all three
- It directly supports the rationale for **NCMM's differentiated, mineral-specific intervention strategy**.

Machine Learning Based

Forecasting and Strategic Insights







Lithium: High Volatility with Strategic Price Sensitivity

The lithium forecast indicates **continued volatility in import values**, reflecting India's near-total dependence on external suppliers.

- **Short-term forecast (12 months):** Elevated import values persist, driven by EV battery demand and global price sensitivity.

- **Medium-term forecast (2–3 years):** A moderation in import values is projected; however, uncertainty remains high.

- **Model performance:**
  The model achieves relatively strong validation accuracy, indicating reliable short-term projections, though medium-term forecasts remain sensitive to price shocks.

Insight:
Lithium remains a **high-risk strategic mineral**, with forecast uncertainty underscoring India's vulnerability to global supply chain disruptions and price fluctuations.

Graphite: Sustained Import Dependence with Moderate Predictability

Graphite imports display a **consistently high baseline demand**, aligned with its critical role in battery anodes and industrial applications.

- **Short-term forecast:** Import values remain elevated, closely tracking recent historical peaks.

- **Medium-term forecast:** Imports stabilize at high levels, suggesting persistent structural dependence.

- **Model performance:**
  Forecast accuracy is moderate, reflecting historical volatility and limited domestic substitution.

Insight:
Despite relatively stable medium-term projections, graphite exhibits **concentration and supply-chain risk**, reinforcing the need for diversification and domestic processing capacity.

Copper: Structurally Rising Demand with Lower Forecast Stability

Copper forecasting reflects **strong structural demand growth**, driven by electrification, renewable energy, and infrastructure expansion.

- **Short-term forecast:** Import values continue to rise, closely aligned with historical upward trends.
- **Medium-term forecast:** Demand remains elevated, with forecasts clustered within a wide uncertainty band.
- **Model performance:**
  Lower R^2 scores highlight the challenge of forecasting copper due to demand shocks, cyclical investment, and global price movements.

Insight:
Copper's forecast indicates **long-term import pressure**, making it a strategic concern despite comparatively better domestic production than lithium and graphite.

Strategic Risk Interpretation

The shaded confidence intervals across all three minerals highlight **zones of elevated strategic risk**, where deviations in global prices, geopolitical events, or demand surges could significantly impact India's trade balance.

- **Lithium:** Highest forecast uncertainty → **critical vulnerability**
- **Graphite:** Stable but concentrated → **supply-chain exposure**
- **Copper:** Rising trend with volatility → **structural import dependence**

Alignment with Problem Statement Objectives

This forecasting exercise directly addresses the competition objectives by:

- Developing **predictive ML-based models** for critical mineral imports
- Generating **short-term and medium-term forecasts**
- Comparing model performance using **MAE, RMSE, MAPE, and R^2**
- Incorporating **confidence intervals** to assess strategic risk
- Translating quantitative outputs into **policy-relevant mineral security insights**

"THE ROLLING STONES"

SAMRUDDHI SADAR

SHASHI PRAKASH MAURYA

SWAYAM KAPILA

ARNAB DEKA

NISHANT CHURIWAL