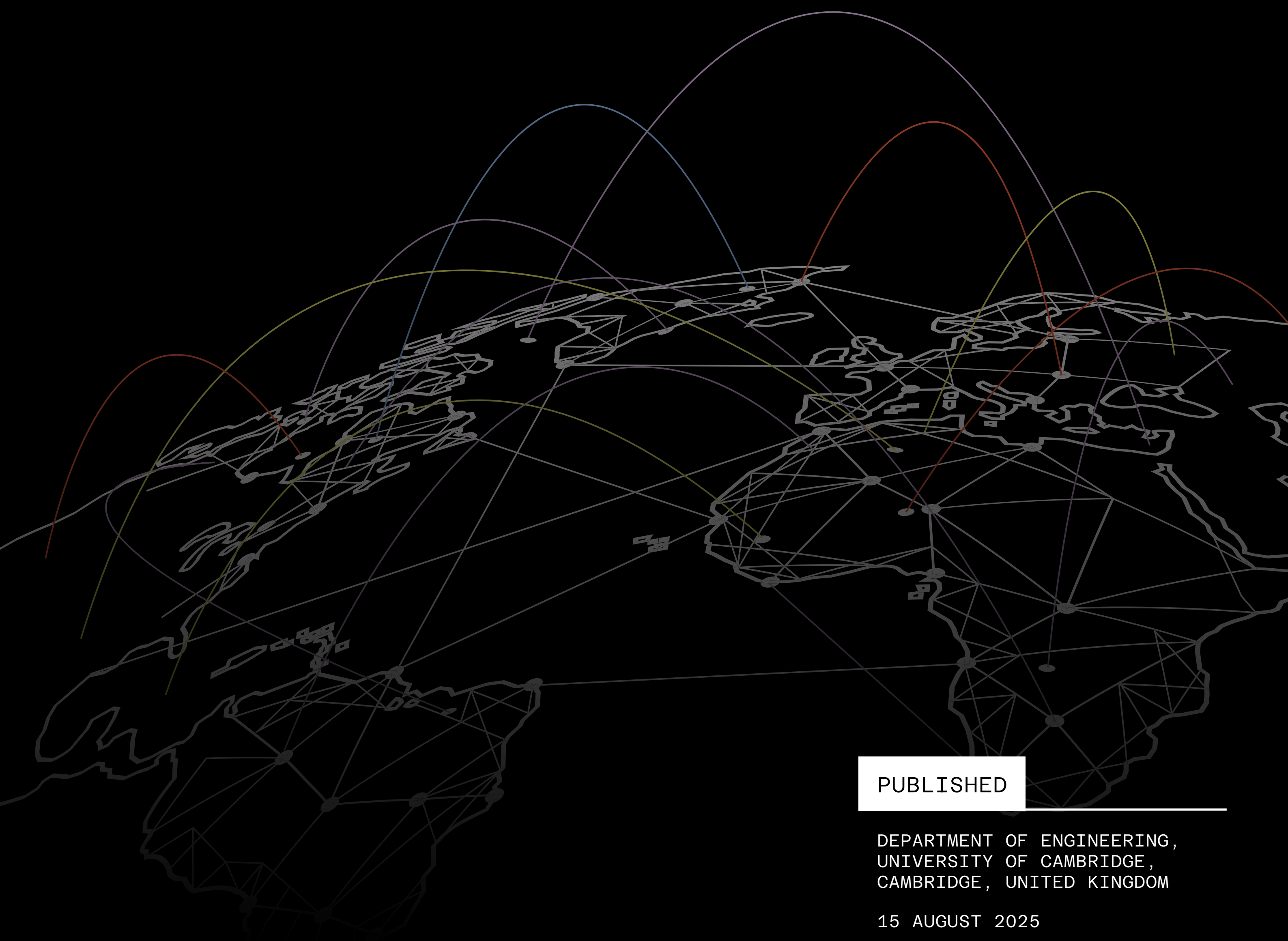
Resilience of Critical Minerals Supply Chain



PUBLISHED

DEPARTMENT OF ENGINEERING,
UNIVERSITY OF CAMBRIDGE,
CAMBRIDGE, UNITED KINGDOM

15 AUGUST 2025

AUTHORS

MEHRNOOSH HEYDARI,
ELLA JENNINGS, HUGH THOMAS,
ANDRÉ CABRERA SERRENHO,
JONATHAN CULLEN

UNIVERSITY OF CAMBRIDGE

PLEASE CITE AS: HEYDARI M, JENNINGS ET, THOMAS H, CABRERA SERRENHO A, CULLEN JM (2025) RESILIENCE OF CRITICAL MINERAL SUPPLY CHAINS. UNIVERSITY OF CAMBRIDGE.

DOI: 10.17863/CAM.123145

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RESEARCH IN THIS REPORT IS FUNDED BY CCG, CLIMATE COMPATIBLE GROWTH: HTTPS://CLIMATECOMPATIBLEGROWTH.COM/ABOUT-US/

EXECUTIVE SUMMARY

Critical Mineral Supply Chains (CMSCs) underpin the global transition to low-carbon technologies and the functioning of strategic industries. They are characterised by a series of interlinked stages—from mining (supply) to refining and transportation (value chain) to end-use, and recycling (demand). Each of these stages is susceptible to unique risks and disruptions. For example, lithium, cobalt, and rare earth elements are sourced from a limited number of countries. This geographic concentration and market complexity present significant challenges for secure and reliable access to CMs.

Various disruptions challenge the stability and long-term viability of CMSCs. Limited reserves, declining ore grades, and the geographic concentration of resources in specific regions raise serious sustainability concerns on the supply side. On the demand side, technological advancements are emerging as influential drivers capable of reshaping market dynamics. Systemic disruptions such as trade restrictions, economic cycles, and political conflicts can affect the entire supply chain. Diversification of suppliers is the most prominent mitigation strategy found in literature, particularly in response to geopolitical instability and supplier monopolies. In addition, strong academic and policy interest in technological interventions—such as recycling infrastructure, circular economy models, and material substitution—reflects their role in reducing reliance on primary extraction. Furthermore, the growing emphasis on international cooperation and trade agreements illustrates the importance of foreign policy in securing continuous material flow and supply chain resilience.

All actors across the CMSCs are exposed to economic, technological, environmental, and social risks, albeit in different ways. Upstream suppliers are particularly sensitive to demand stability, while downstream buyers are susceptible to supply disruptions. Midstream actors, such as processors and refiners, face risks from both sides — making them particularly vulnerable to dual shocks. External shocks such as geopolitical conflict, climate events, and social unrest tend to negatively affect all actors across the value chain. Financial risks, such as price volatility, may have uneven effects — proving advantageous to some while detrimental to others, depending on their position and exposure. **This differentiated risk landscape necessitates targeted resilience strategies for each supply chain segment.**

Clear policies and regulations are key to maintaining the CMSC and minimising risks to it. With increasing clarity on the importance of certain minerals to the low-carbon energy transition, the number of policies and regulations regarding their supply chains has increased exponentially. Governmental policies most often concern the security of CMSCs and also cover environmental, social, and governance (ESG) compliance and retention of domestic ownership of resources. Standards to which CMSCs are held in industry, generally cover their traceability and transparency, and/or standards for ESG. Many international governmental partnerships and agreements now exist to further enhance the security of global supply chains.

This report presents a comprehensive analysis of the resilience of CMSCs, drawing on current disruptions, risk structures, and strategic responses. The insights aim to support decision-makers across government, industry, and academia in formulating targeted interventions that address systemic risks and promote the long-term sustainability of CMSCs.

CONTENTS

Further risks to supply chains are due to disruptions to freight transport. Blockages and water shortages can create bottlenecks around the Panama and Suez canals and conflicts can create security challenges for international shipping. For example, recent attacks on commercial vessels in the Red Sea have decreased transits through the Suez Canal by an estimated 42%, compared to its historical peak. [48]

The resilience of CMSCs is key to economic growth and political stability at national, international, and global scales. Since demand for CMs is increasing, and risks on the system are unpredictable, governments and industries enact policies and regulations to minimise the risk posed to their economy. These are in the form of policies, government action plans, international partnerships and agreements, and industry standards. This section catalogues these regulations from around the globe and considers their aims and objectives in maximising CMSC resilience.

Introduction

Modern technologies—from electric vehicles (EVs) and advanced electronics to renewable energy systems (e.g., wind turbines, solar panels) and defence applications—rely heavily on critical minerals (CMs),[1] including rare earth elements, lithium, cobalt, graphite, and nickel. EVs, for instance, require significantly more minerals than conventional internal combustion vehicles. Projections indicate that the demand for copper and nickel could nearly double by 2050, while lithium demand may increase 32-fold.[2] CMs' strategic role in the energy transition and for national securities has intensified global attention on their accessibility and control.[3,4] However, the supply chains that deliver these minerals are increasingly vulnerable to complex and systemic disruptions.

The supply chains for CMs are highly complex, geographically concentrated, and exposed to various risks. For example, the Democratic Republic of the Congo dominates global cobalt reserves,[5] Australia and Chile lead in lithium,[6] and China holds the largest share of natural graphite.[7] This geographical concentration underscores the strategic importance of certain countries in the global supply network and exposes these chains to significant vulnerabilities. Geopolitical tensions, market volatility, environmental concerns, and operational challenges can disrupt the steady flow of these essential materials. Given these structural vulnerabilities, enhancing supply chain resilience has become a policy priority for many governments. Supply chain resilience is the ability of a supply chain to maintain, resume and restore operations after a disruption.[8]

The resilience of CMSCs is crucial for economic growth, industrial development, and geopolitical stability. As demand for these minerals rises and supply chain risks become increasingly threatening, governments and industries have introduced policies, action plans, international agreements, and industry standards in an attempt to safeguard access to these essential resources. Historically, mining policies focused on economic regulation and safety, but recent policies emphasise supply chain security and sustainability, particularly for the low-carbon energy transition. International partnerships strengthen resource flows between mineral-rich and industrial nations, while industry-led environmental, social, and governance (ESG) frameworks promote responsible sourcing. There is little consistency in policies and standards across different countries and for varying CMs. It is important to consider how policies, partnerships and standards can harmonise efficiently to increase the resilience of CMSCs across the globe.

This report aims to integrate these fragmented insights into a comprehensive analysis—addressing risks and disruptions, mitigation measures, and global policy coordination—to form an integrated view of supply chain resilience.

Overview of the Critical Minerals Supply Chains

CMSCs are inherently complex, consisting of interconnected stages—from exploration and mining, through processing and refining, and into high-tech manufacturing and end-use (Figure 1). Understanding the vulnerabilities across these stages is essential to identifying and mitigating potential disruptions.

A. SUPPLY STAGE: EXPLORATION AND MINING

At the upstream end, exploration and mining activities are primarily concentrated in resource-rich regions. These activities are sensitive to a range of factors, including local geopolitics,[9–11] regulatory frameworks,[12–14] and environmental concerns.[15,16] For example, cobalt, lithium, and graphite deposits are concentrated in regions subject to political and economic uncertainties, making the initial stages of the supply chain vulnerable to geopolitical disruptions.

B. VALUE CHAIN STAGE: PROCESSING AND REFINING

Raw minerals require processing and refining following the mining stage—a midstream segment where technological capability and infrastructure investments are critical. Here, any disruption (e.g., due to logistical challenges or regulatory shifts) can have cascading effects on downstream industries. Inefficiencies in processing can significantly undermine overall supply chain robustness.[17] This highlights the critical importance of technological innovation, resilient infrastructure, and effective regulatory frameworks to sustain continuous mineral flows and high processing efficiency.

C. DEMAND STAGE: MANUFACTURING AND DOWNSTREAM INTEGRATION

This stage is characterised by rapidly changing market demands driven by technological innovation and global decarbonisation goals. Fluctuating demand patterns, and upstream and midstream supply uncertainties create significant operational and strategic challenges for manufacturers. CMSCs form a global network, resulting in an interconnected vulnerability to disruptions caused by environmental regulations, labour disputes, and geopolitical conflicts.[1]

The complex connectivity between these stages necessitates a holistic approach to disruption management and resilience-building. A detailed examination of supply chain disruptions, their categorisation, and associated mitigation strategies, provided in the subsequent sections, addresses this need by outlining specific vulnerabilities and proposing targeted interventions for enhancing supply chain resilience.

FIGURE 1

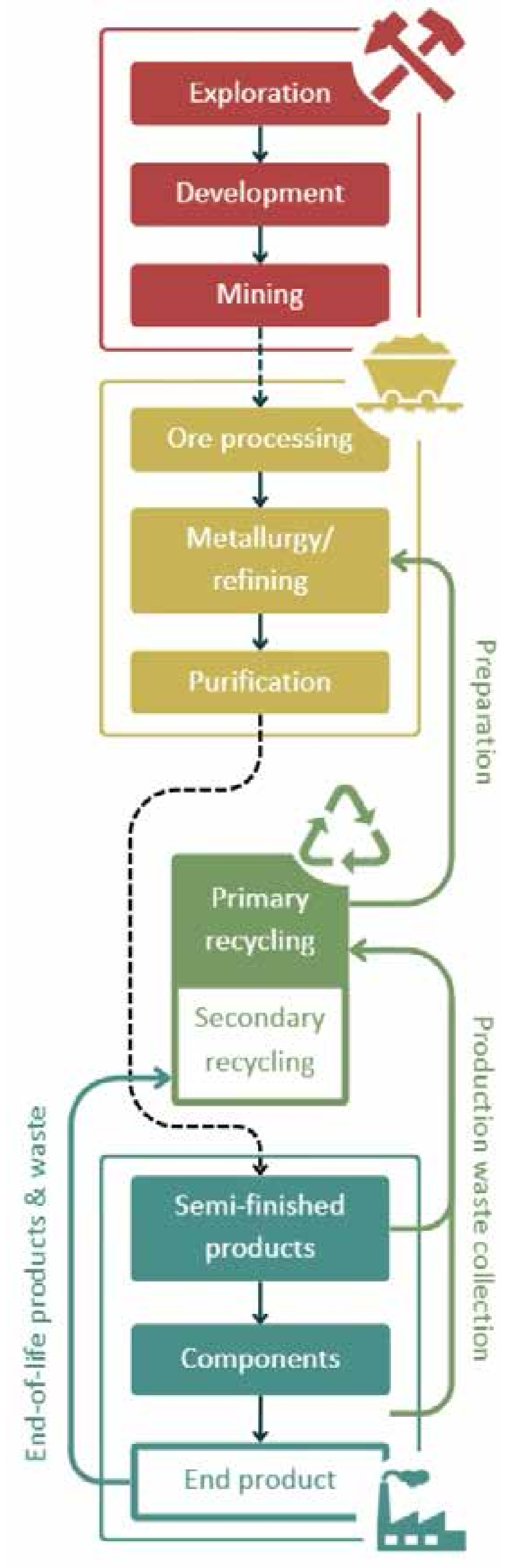


FIGURE 1. SCHEMATIC REPRESENTATION OF A CRITICAL MINERAL SUPPLY CHAIN[18]

Disruptions and Mitigation Measures across the Supply Chains

KEY TAKEAWAYS

→ Supply-side key challenges include limited resources, declining ore grades, and geographic concentration.

→ Technological advancements influencing demand receive little emphasis in academia, yet they possess the potential to significantly reshape market trends.

→ Disruptions affecting the entire CMSCs, such as trade restrictions, economic cycles, and geopolitical conflicts, reveal the interconnectedness and vulnerabilities of supply chains.

→ Diversification is recognised as the primary strategy for mitigating risks in the CMSCs, with a focus on geographic and supplier diversification to address vulnerabilities from geopolitical instability and resource monopolies.

→ There is strong scholarly interest in technological solutions, such as recycling infrastructure and material alternatives to enhance resilience by reducing dependence on primary mineral extraction.

→ Attention to international cooperation highlights the significance of policy in reducing trade barriers to ensure a steady flow of minerals across the CMSC.

A comprehensive and systematic review of the existing academic literature has been conducted, encompassing 327 peer-reviewed articles published between 2015 and 2025. This extensive review facilitated the identification, categorisation, and analysis of disruptions to CMSCs and subsequent mitigation measures. The analysis categorises these disruptions and corresponding strategies to provide stakeholders with a detailed understanding of key vulnerabilities and effective interventions. This classification aims to enhance the clarity and applicability of research findings, aiding policymakers, industry leaders, and researchers in formulating informed, resilient, and adaptive strategies.

This research categorises the reviewed literature into four primary groups based on their coverage of the CMSCs: (1) Supply, (2) Value Chain, (3) Demand, and (4) All three stages (the entire supply chain). Figure 2 presents the proportional distribution of the literature according to the stages they cover. The largest share (50.5%) of scholarly attention has been dedicated to research covering the entire supply chain. 26.5% of studies specifically address disruptions and/or mitigation measures at the supply stage, which underscores a considerable focus on upstream challenges such as resource scarcity, geopolitical risks, and extraction difficulties.

In comparison, studies focusing exclusively on the value chain constitute a smaller yet significant share (18.8%), indicating attention toward midstream activities including processing, refining, and manufacturing. Notably, only 4.2% of the reviewed articles concerned the demand stage. This reveals a scholarly gap regarding the impacts of end-market fluctuations, technological advancements, and changing consumption patterns on the resilience of CMSCs. Future research should explore opportunities for mitigating disruptions which originate at the demand end of CMSCs. Table 1 presents a heatmap illustrating the frequency with which different CMs are examined across various supply chain stages in the 327 reviewed articles. The analysis reveals a strong research emphasis on the full supply chains of REEs, cobalt, lithium, and copper, some emphasis on their supply and value chain stages, and relatively low emphasis on the demand end. Additionally, several CMs essential to the energy transition—such as manganese and graphite—remain significantly understudied. This highlights a key gap in the existing literature and points to important opportunities for future research.

The following subsections offer detailed discussions and analyses of the identified disruptions and their associated mitigation strategies across CMSCs.

FIGURE 2

DISTRIBUTION OF STUDIES BY SUPPLY CHAIN STAGE

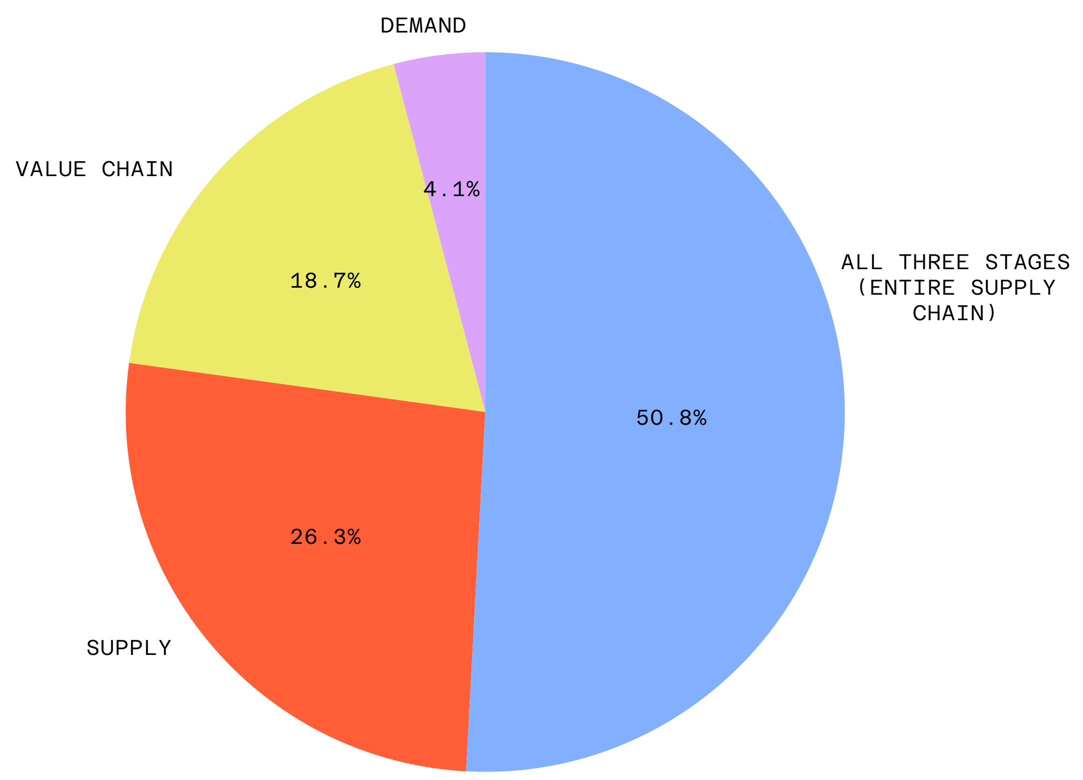


FIGURE 2. SUPPLY CHAIN STAGE COVERAGE ACROSS 327 REVIEWED ARTICLES (2015-2025)

TABLE 1

Supply Chain Stage vs Minerals Frequency in 327 Articles Reviewed

Minerals	All three stages	Supply	Value Chain	Demand	Total
Critical Minerals	47	20	12	8	87
Arsenic	2	0	1	0	3
Boron	2	1	1	0	4
Cadmium	5	5	2	0	12
Chromium	8	5	3	0	16
Cobalt	68	22	16	9	115
Copper	43	10	7	2	62
Dysprosium	12	1	7	2	22
Gallium	25	4	3	0	32
Germanium	8	5	3	0	16
Graphite	9	2	5	2	18
Hafnium	1	0	0	0	1
Indium	13	7	5	0	25
Iridium	1	1	0	0	2
Lead	1	2	2	1	6
Lithium	52	24	17	7	100
Magnesium	6	0	1	0	7
Manganese	16	7	4	4	31
Molybdenum	11	3	2	1	17
Neodymium	16	4	12	1	33
Nickel	32	10	13	7	62
Niobium	7	5	3	0	15
Phosphorus	3	1	2	0	6
Platinum	18	8	4	9	39
Praseodymium	8	0	3	1	12
Rare earth	72	23	27	4	126
Selenium	6	2	1	0	9
Silicon	4	0	1	0	5
Silver	12	3	3	1	19
Tantalum	8	9	2	1	20
Tellurium	14	1	4	0	19
Terbium	4	0	0	0	4
Tin	3	5	1	1	10
Titanium	7	3	3	3	16
Tungsten	6	1	3	0	10
Vanadium	8	3	3	0	14
Zinc	6	5	1	1	13
Zirconium	1	0	1	0	2
Total	565	202	178	65	1010

Supply Chain Stage

TABLE 1 FREQUENCY OF MINERAL TYPES ASSESSED ACROSS THE SUPPLY CHAIN STAGE IN 327 ARTICLES REVIEWED

Supply Chain Disruptions

A comprehensive classification has been established to provide a structured overview of disruptions within CMSCs, encompassing seven primary categories, 19 subcategories, and 41 distinct sub-subcategories (Table 2). These sub-subcategories are colour-coded based on their primary impact along the CMSCs: supply (red), value chain (yellow), demand (orange), combined supply and value chain (green), or all three stages (blue). Figure 3 illustrates the main disruption categories along with the frequency of their mentions across the review of 327 scholarly articles.

Within the supply-stage, limited resource/reserve is discussed most frequently across 327 reviewed papers (89 mentions), followed by declining ore grades (50 mentions) and then geographic concentration (23 mentions). This significant academic attention to geological and physical constraints related to raw mineral extraction, highlights critical long-term sustainability issues within the upstream supply chain.

Demand-side disruptions, specifically change in demand due to technological advancements, received less emphasis with relatively fewer mentions (23). Nevertheless, these **sudden market shifts—such as new battery technologies or alternative energy innovations—can profoundly reshape demand patterns,** reinforcing the need for comprehensive and integrated supply chain analyses.

Export/import bans (79 mentions), boom-bust cycles (72 mentions), and armed conflicts (60 mentions), disrupt all stages of the CMSC and have attracted substantial scholarly focus. These systemic risks underscore trade restrictions, cyclical price volatility, and geopolitical instability as factors capable of cascading through the entire supply chain. Policy-driven disruptions also discuss all stages disruptions, i.e., tariffs and quotas (20 mentions), sanctions (10 mentions), and regulatory restrictions (8 mentions).

The analysis indicates that Production Constraints and Geopolitical & Policy Disruptions have received significant scholarly attention. In contrast, the existing academic literature has comparatively under-assessed categories such as Infrastructure & Logistics Disruptions, Natural Disasters & Climate-Driven Disruptions, and Operational & Technological Disruptions.

FIGURE 3

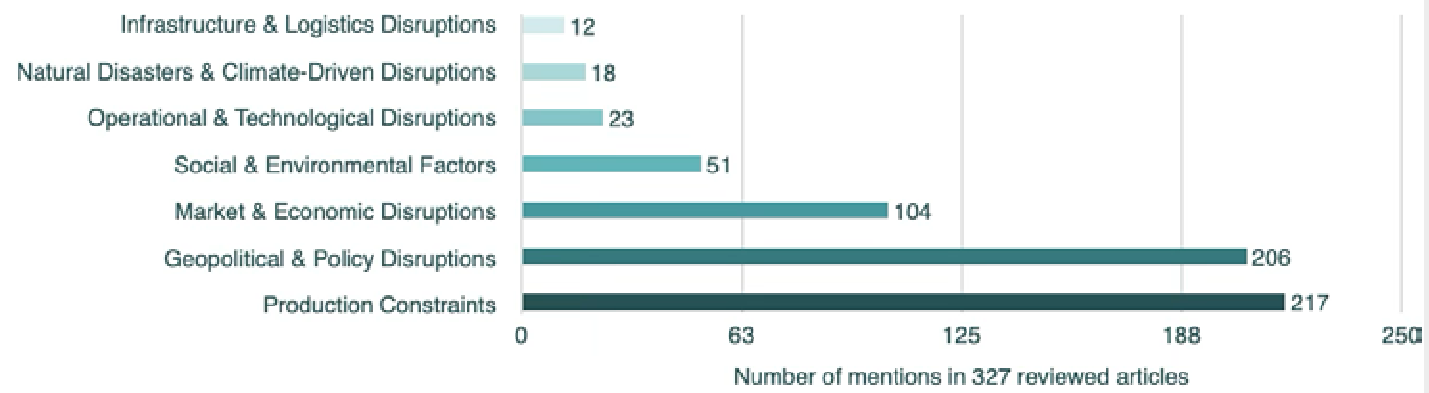


FIGURE 3. DISRUPTION CATEGORIES AND FREQUENCY OF MENTIONS ACROSS 327 REVIEWED ARTICLES.

MAIN CATEGORY	SUBCATEGORY	SUB-SUBCATEGORY
Geopolitical & policy disruptions	Trade & regulatory restrictions	Export/import bans
		Tariffs, Quotas
		Sanctions
	Political Instability & Conflict	Regulatory restrictions
		Armed conflicts
		Regime changes
	Resource Nationalism & Expropriation	Licensing & Regulatory Shifts
		Government asset seizures
		Mandatory domestic ownership
Market & economic disruptions	Price volatility & supply-demand imbalance	Boom-bust cycles
		Market speculation
		Demand change
	Recession & Industrial Downturn	Supply chain bankruptcies
Infrastructure & logistics disruptions	Port & transport disruptions	Port/road blockades
		Physical damage/ sabotage
	Energy Supply Disruptions	Power outages
		Fuel shortages
	Infrastructure Failures	Pipeline/Port/Rail sabotage or failure
Operational & technological disruptions	Equipment & technological failures	Machinery failures
		Tailings dam failure
	Health & Safety Incidents	Safety incidents (accidents)
		Health issues like pandemics
	Labour Strikes & Workforce Issues	Wage disputes & labour strikes
		Skilled labour shortages
Natural disasters & climate-driven disruptions	Geological & meteorological events	Earthquakes, tsunamis, landslides
	Climate Change Impacts & Extreme Weather Events	Rising temperatures, water scarcity
		Hurricanes, Floods, Wildfires
Social & environmental factors	Community & legal challenges	Protests, legal injunctions, unequal benefits
	Environmental & ESG Pressures	Waste disposal restrictions, carbon limits
		Reputational risk
	Human Rights & Social Issues	Child labour, Forced labour
Production constraints	Supplier consolidation & monopoly	Supplier monopoly power
		Geographic concentration
	Mining & processing constraints	Declining ore grades
		Limited resource/reserve
		Processing complexity
		Mine closure (Temporarily or Permanently)
		Small-scale mining issues
		By-product production complexities in the mining & processing stage
	Limited secondary supply (Urban mining, Recycling)	Technological limitations
		Recycling inefficiencies

KEY
- SUPPLY STAGE MITIGATION MEASURES
- VALUE CHAIN STAGE MITIGATION MEASURES
- DEMAND STAGE MITIGATION MEASURES
- SUPPLY & VALUE CHAIN STAGES MITIGATION MEASURES
- ENTIRE SUPPLY CHAIN MITIGATION MEASURES

TABLE 2. DISRUPTIONS OF CMSCS BASED ON LITERATURE REVIEW (327 PEER-REVIEWED PAPERS PUBLISHED BETWEEN 2015 AND 2025)

Supply Chain Mitigation Measures

This subsection examines a comprehensive set of strategies designed to mitigate disruptions within CMSCs. By consolidating and categorising measures drawn from peer-reviewed literature, the report synthesises these strategies into seven main groups. Each mitigation measure is further annotated with a colour-coded indicator corresponding to its applicable stage in the supply chain—supply, value chain, both supply and value chain, or all three stages—highlighting its integration and targeted impacts within the global supply network (Table 3).

Diversification is the most mentioned strategy for mitigating CMSC risks.

Figure 4 illustrates the frequency of mentions for each strategic category, underscoring varying scholarly emphasis. Diversification & alternate sourcing received the highest attention (225 mentions), clearly highlighting its recognition in literature as the predominant strategy for mitigating CMSCs risks. Specifically, geographic diversification and supplier diversification can reduce vulnerabilities arising from geopolitical instability and resource monopolies. Similarly, **alternative suppliers & sub-suppliers (71 mentions) were frequently highlighted, reinforcing the importance of sourcing diversification across different supplier tiers.**

Technological & process innovation, mentioned 163 times, emerges as the second most discussed strategy, indicating strong scholarly interest in technological solutions such as recycling infrastructure (75 mentions) and material alternatives (53 mentions). Such innovations are perceived as crucial for enhancing resilience, especially within the value chain segment. These innovations reduce reliance on primary mineral extraction and mitigate vulnerabilities associated with resource scarcity.

Policy-oriented strategies, such as bilateral/multilateral free trade agreements (32 mentions), indicate scholarly belief that international cooperation and policy mechanisms are essential means to reduce trade barriers and ensure continuous mineral flow across the entire supply chain.

The predominance of geographic diversification and alternative sourcing strategies demonstrates a strong academic consensus regarding the critical importance of managing geopolitical risks at the supply stage. Given frequent disruptions such as export restrictions and regional concentration of resources, this emphasis on diversified raw material sources is well-justified.

The substantial focus on recycling infrastructure highlights an evolving acknowledgement of circular economy practices as integral to achieving long-term value chain resilience. By enhancing recycling capabilities, industries can significantly reduce dependency on primary extraction and better address constraints such as declining ore grades and resource scarcity. Concurrently, the prominence of material substitution reflects scholarly awareness that technological innovation can effectively mitigate risks associated with mineral shortages or monopolistic market structures.

Lastly, although less prevalent, the recognition of free trade agreements underscores the ongoing acknowledgement of global collaboration and policy intervention as critical systemic measures. It reinforces the notion that **robust resilience strategies require multi-dimensional solutions, combining diverse sourcing approaches, technological innovation, and international cooperation frameworks to comprehensively address supply chain disruptions.**

MAIN CATEGORY	SUBCATEGORY	SUB-SUBCATEGORY
Diversification & alternate sourcing	Geographic diversification	Multiple countries/regions
		Multiple mines/companies
	Alternative sourcing	Alternative suppliers & sub-suppliers
		Supplier development programs
		Sea-bed mining
	Nearshoring/onshoring	Regional processing plants
		Local partnerships
	Stockpiling & inventory	Government strategic reserves – stockpiles
		Allied agreements
		Corporate buffer inventories
		Storage & warehousing strategies
Policy, regulatory & market mechanisms	Trade & alliances	Bilateral/multilateral free trade agreements
		Strategic alliances
		Tax credits for local production
	Export controls & monitoring	Controlled exports of key inputs
		Real-time tracking
	Harmonized standards & regulations	ESG criteria alignment
		Clear permitting processes
	Market mechanisms & transparency	Offtake agreements
		Spot vs. long-term balance
		Secondary resource markets
		Price discovery mechanisms
		Regular market intelligence
Technological & process innovation	R&D & substitution	Material alternatives
		Alloy innovations
	Recycling & circular economy	Recycling infrastructure
		Secondary source mining/ Urban mining
	Efficiency & digitalization	Advanced processing/refining technologies
		Reducing unit costs
		Exploration accuracy
		Supply chain mapping & simulation
Infrastructure & logistics resilience	Transport networks	Multi-modal options
		Choke point mitigation
	Port & facility upgrades	Capacity upgrades
	Energy & water security	On-site power generation
ESG & sustainability	Traceability & certification	Blockchain/digital tracking
		Certification standards
	Community & environmental engagement	Benefit-sharing agreements
		Cultural & environmental protections
	Sustainable mining practices	Lifecycle planning
		Sustainable mine closure & rehabilitation
Risk management & business continuity	Scenario & contingency planning	Complex disruption simulations
		Customized contingency plans
Collaboration, alliances & workforce development	Partnerships & consortia	Shared technology & expertise
		Information-sharing networks
		Multilateral platforms
		Coordination on supply chain security
	Workforce development & labour relations	Upskilling local workforce

KEY

SUPPLY STAGE MITIGATION MEASURES
DEMAND STAGE MITIGATION MEASURES
ENTIRE SUPPLY CHAIN MITIGATION MEASURES
VALUE CHAIN STAGE MITIGATION MEASURES
SUPPLY & VALUE CHAIN STAGES MITIGATION MEASURES

TABLE 3. MITIGATION MEASURES FOR CMSCS RESILIENCE BASED ON LITERATURE REVIEW (327 PEER-REVIEWED PAPERS PUBLISHED BETWEEN 2015 AND 2025)

FIGURE 4

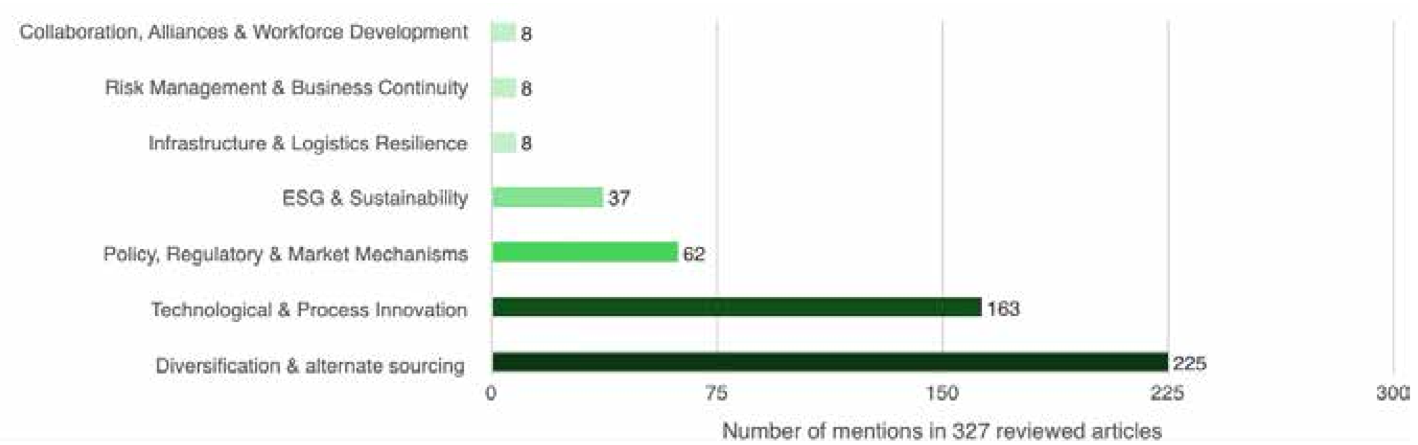


FIGURE 4. MITIGATION STRATEGIES CATEGORIES AND FREQUENCY OF MENTIONS ACROSS 327 REVIEWED ARTICLES.

Risk Analysis

KEY TAKEAWAYS

→

All actors in critical mineral supply chains are susceptible to economic, technological, environmental and social risks.

→

Buyers and suppliers of CMs are typically most vulnerable to risks that affect stable supply and demand respectively.

→

Mid-stream actors are uniquely exposed to risks that disrupt both stable supply and demand.

→

Social, environmental and external shocks typically act detrimentally to all actors, whereas financial risks can be beneficial to some actors whilst being detrimental to others.

FIGURE 5

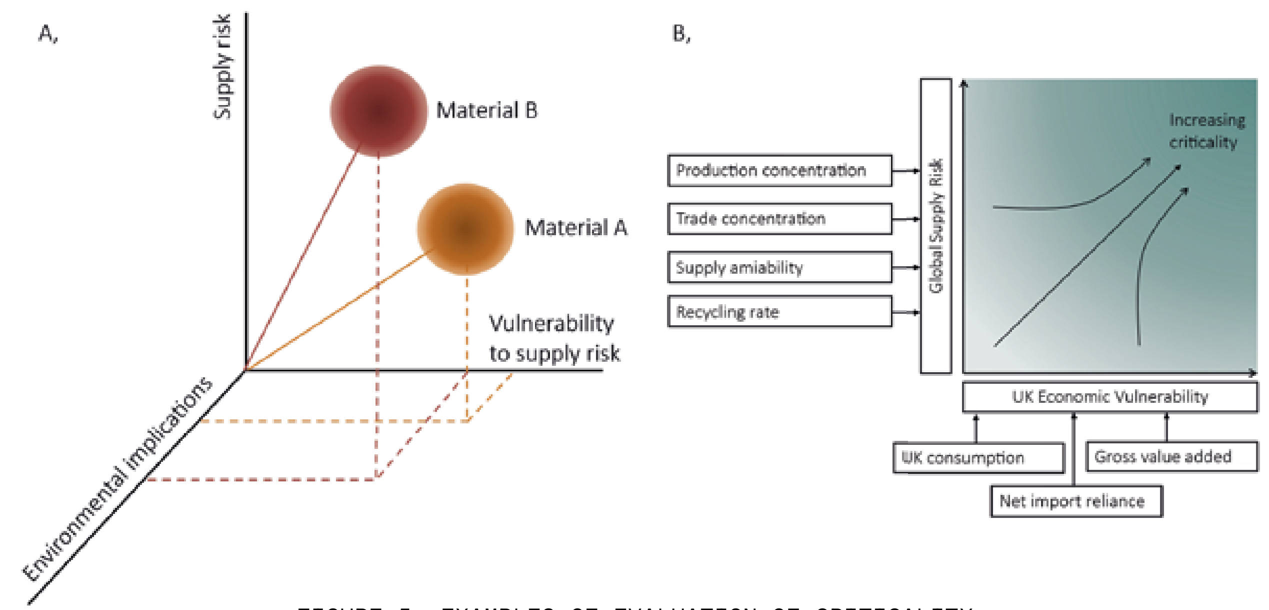


FIGURE 5. EXAMPLES OF EVALUATION OF CRITICALITY. A, ADAPTED FROM [19]; B, ADAPTED FROM [20]

The degree of criticality refers to the importance of a material to an industry or economy, based on supply risks, vulnerability to supply disruptions and ecological considerations. Supply chain risk is the possibility of an event occurring that causes disruption to a supply chain. Susceptibility to these disruptions can be quantified by the degree of material criticality, usually formulated as a function of supply risk (the possibility of supply chain disruptions) and the potential impacts of the disruption (vulnerability to the risk). Figure 5 shows two such formulations of criticality, with criticality defined by the length of the vector in figure 5A and defined as an index of risk multiplied by vulnerability in figure 5B. CMs have high degrees of criticality, meaning that their supply chains are particularly prone to disruptions compared with supply chains with high levels of diversity, redundancy and resilience. Risks are present at all stages of CMSCs (Figure 1), with disruptions at each stage potentially exposing different supply chain actors. Here we review CMSC risks, by summarising the main risks for each type of supply chain actor.

Risks to buyers

CMs are an important component of many rapidly proliferating energy technologies, such as electricity networks, EVs, wind turbines and solar panels.[21] As such, the number of buyers whose business relies on being able to access CMs is expected to grow, increasing CM demand. Despite the many studies that predict increased CM use, projecting future demand for CMs is characterised by large uncertainties and for some high criticality metals demand projections do not exist at all.[22] In this section, we review the risks to the buyers of CMs that will drive this increasing demand.

SUPPLIER GEOGRAPHIC CONCENTRATION

Given the geographical distribution of CMs globally, some CMs supply is exclusively from either single countries or a small number of countries. This creates supply chains with single points of failure where there are no backup or redundant options available. Furthermore, it can reduce competition and lead to monopolies and oligopolies, which can allow countries to exert significant influence over prices and output, and lead to high barriers to entry for new competitors. Formal cartelisation is also a risk, when sufficient proportions of total resources are held by cooperating countries and companies. Despite the risks to buyers, cartelisation can benefit supplying countries as profits can be maximised through coordination of production, pricing and market allocation.[23]

Geographically concentrated CM supply (Figure 6) can limit domestic production in countries with no or inaccessible resources. Furthermore, there are limited prospects for immediate production at scale where CMs assessments are at the stage of identifying prospective areas for further exploration into mineral deposits, thus continuing reliance on imports.[23]

TRADE RESTRICTIONS

Trade regulations can also impact the availability and costs of CMs across the supply chain. Trading restrictions can disrupt established supply chains and trade patterns, leading to uncertainty, price changes and reduced material availability.[25] There is currently a precedent for countries and trade blocs to impose trade restrictions on raw and processed minerals. China placed restrictions on antimony exports and mandated licences for gallium and germanium export in 2023[20]; the USA's Inflation Reduction Act (IRA) offered tax credits for sourcing CMs for clean energy technologies domestically or from countries with free trade agreements [26]; and in 2024, the EU introduced the Critical Raw Materials Act, which targeted keeping annual consumption from a single production source below 65%.[27] Trade restrictions are often established to reduce dependence on a single source and diversify supply chains as well as a means of exerting geopolitical influence over other countries. Geopolitical tensions can also provide incentives for resource stockpiling, particularly for minerals required for defence industries.[28]

FINANCIAL MARKET RISKS

An unstable supply of CMs can cause price fluctuations. This can lead to supply chain instability, budget uncertainties and potential financial losses for both buyers and suppliers, depending on the direction of the price change.[29]

Risks to suppliers

Critical raw mineral supply must initially be met through mining. The location of mineral deposits is dependent on geological formations. However, the decision to exploit the mineral deposits is dependent on other considerations, including the economic incentives and social, environmental and legal considerations.[24] The useful products of mining operations can be classified into 3 main categories: major commodities, co-products and by-products. Co-products are raw materials that are produced alongside the major commodities and contribute to the economic viability of mining a deposit. Conversely, by-products are usually found in concentrations of <0.1% and rarely form viable deposits on their own, but instead occur interstitially in the ores of metals with similar chemical and physical properties.[30] Most CMs currently listed in the UK criticality assessment are typically mined as co-products or by-products of ore forming minerals. Despite the projected demand growth for many CMs, by-product production is unlikely to be increased by suppliers as the return on investment is not high enough.[31] However, technology development and market conditions can change, altering the value of mining and creating risks for CM suppliers.

COUNTRY CONCENTRATION

Countries with abundant or highly concentrated natural resources do not automatically benefit from the economic opportunity to mine, process and export CMs. This risk is often termed the resource curse and emerges in countries with institutions that do not support producer friendly supply chains to form and in countries with undemocratic political regimes. To benefit fully from their natural resources countries must have institutions and political incentives that are conducive to the redistribution of export income and the stable long-term development of supply chains.[32]

Exporting countries can become reliant on demand from other markets. This market dependence can expose domestic markets to economic conditions and the fiscal policy of other countries. Less developed exporting countries are also susceptible to power imbalances in CM markets. For example, industrialised countries can dominate the decision-making process when assessing the economic value of mine sites and negotiating off-take and tax agreements. Furthermore, economic stagnation and recessions in other countries can lower export demand, causing cascading effects such as lowering incomes from falling commodity prices. Trade restrictions may also limit export opportunities. Trade restrictions, such as tariffs, sanctions and embargoes, can be implemented by importing countries for a variety of reasons including attempting to protect domestic industries, exerting pressure on exporters for geopolitical reasons and enforcing constraints related to responsible sourcing that require adherence to laws surrounding human rights and sustainability.[2]

COMPANY CONCENTRATION

Risks arising from concentrated production can also arise when the supply chain is controlled by one or a small number of companies operating in multiple countries.[2] Similar to country concentration, company concentrations can lead to risks associated with monopolies and oligopolies, where a small number of suppliers dominate the industry and exert significant control.

BY-PRODUCT COMPLEXITIES

Currently many CMs are recovered as by-products from the mining operation of other minerals. For example, cobalt can be obtained from nickel and copper mining, gallium from aluminium or zinc refining, and tellurium from copper refining.[2] As by-products are not the main target of mining operations, by-product yields are susceptible to changes to the incentives for mining the primary target mineral. This introduces an additional level of risk and dependence on major commodity material supply chains, which share many of the same risks as CMSCs, such as trade restrictions, supply chain bottlenecks and operational risks.

FIGURE 6

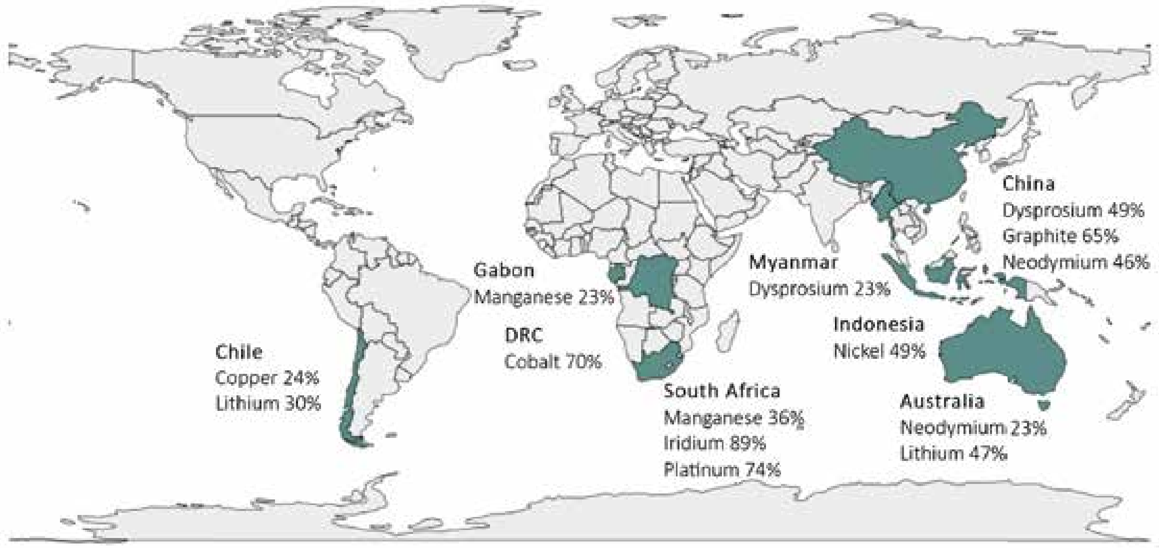


FIGURE 6. COUNTRIES WHERE MINING CONCENTRATION OF CMS IS ABOVE 20%. DATA FROM [23]

MATERIAL SUBSTITUTABILITY

Buyers of CMs are less vulnerable to supply risks if alternative materials can be used for the same purpose. Conversely, suppliers are susceptible to a significant risk of reduced demand if technological developments lead to substitution opportunities. For example, sodium ion batteries are under development as a potential alternative to lithium ion batteries. [2]

CMS FROM SECONDARY SOURCES

Finding and exploiting secondary sources of CMs can reduce the demand for primary CMs. There is currently very limited data on the potential stocks of CMs that could be obtained from secondary sources. Recycling can increase the value of end-of-life products and mitigate some of the risks associated with concentrated supply chains as it diversifies the CM sources. However, there are significant challenges to recycling CMs. Around 1% of REEs are recycled from their end products, such as from permanent magnets, batteries and catalysts.[33] Further, mismatches between demand and the supply of end-of-life products limits the available stocks from which resources can be recovered. For example, EV battery recycling capacity is expected to be in overcapacity by 2030, with supply of end-of-life EV batteries only accounting for 1/3 of total possible recycling input.[34] CMs could also be produced from processing historical mine waste dumps, where CM extraction was previously not economically viable, but as the price of these minerals increases, these waste dumps can be considered as a secondary source.[35]

ESG (ENVIRONMENTAL, SOCIAL AND GOVERNANCE) RISKS

CMs are vital to many renewable energy and decarbonisation technologies, including solar panels, wind turbines, electricity networks and EV batteries. Bottlenecks in the deployment of these technologies due to CM supply risks could slow down the energy transition, meaning that fossil fuels use continues for longer.[23] Uncertain CM availability could also lead to lock into high carbon pathways, where continued investment in long lifetime fossil fuel infrastructure can lead to stranded assets and increase the costs of future shifts towards low carbon technologies. Further environmental risks from mining exist at a more local level. Deforestation and biodiversity loss can occur from changing land use to access mineral deposits, heavy metal pollutants can be released into the environment contaminating water supplies, and air pollution can be caused by mining activities.[36]

Mining can also exacerbate and reinforce social problems. Unregulated artisanal and small-scale mining, such as that of cobalt in the Democratic Republic of the Congo, has well documented issues with child labour, unequal wealth distribution, forced relocation, and modern slavery.[37] Corruption can mean that the benefits of mining are not passed onto the labour force equitably and inadequate labour and social protection laws mean that working conditions do not improve.[36] Social issues associated with CM mining often do not impact all social groups equally. For example, 54% of minerals reserves required for the energy transition are located within or near indigenous people's lands.[38] Displacement of these communities can lead to loss of land and natural resources that are essential to their livelihoods and cultural practices.[39]

OPERATIONAL RISKS

As demand for CMs increases, mining operations will grow, with greater investments in mechanisation, digitalisation and automation. Increasing the complexity of mining operations can introduce new areas of risk. For example, digital and autonomous systems can be susceptible to cybersecurity risks.[40] Further disruptions to operations can come from health and safety, legal and political, and (mis)management risks. Health and safety incidents can disrupt operations; compliance and regulatory requirements can delay operations; and management risks including labour disputes and shortages can all limit production capacities.[41] There are also technological risks that can impact the economic viability of mining. Geological conditions, geotechnical risks, such as landslides, and inadequate mineral prospecting can all limit the feasibility of mining in a certain area.[41]

Risks to value chain and midstream actors

Buyers of CMs purchase both raw minerals and end-use products containing CMs. Typically, there are several actors involved in the intermediate stages through which raw minerals are converted into useful products and end-of-life stages where products are eventually disposed of (Figure 1). Here we explore some of the risks to the actors involved in transforming CMs along product value chains. Where the risks to buyers and suppliers typically stem from concentrated supply and demand respectively, midstream actors' intermediate positioning makes them uniquely susceptible to both supply and demand disruptions.

SUPPLY CHAIN BOTTLENECKS

A bottleneck is considered to be the point in a value chain for a specific mineral where the supply risk is the highest.[42] Bottlenecks can occur when midstream processes are concentrated in single areas. For example, intermediate products for wind turbine and traction motor production, such as polysilicon, silicon metal and silver paste, are largely located in China, meaning a single disruption can delay the critical path of production.[43] Further, trade restrictions, such as export controls, import restrictions and geopolitical sanctions, can exploit bottlenecks. Bottlenecks can also form because of rapid increases in demand. Global lithium demand, for example, is anticipated to require a 32-fold increase compared to current supply by 2030 to avoid a market deficit.[43] This will require the rapid development of value chain infrastructure. This will be difficult to achieve given mines coming into the supply chain between 2010 and 2019 took on average 16 years to transition from mineral exploration to initial production.[44]

EXTERNAL SHOCKS

Supply chains are also susceptible to external shocks, such as extreme weather events. Copper and lithium mining are particularly vulnerable to water stress caused by droughts and climate change affecting river flows, due to their high water requirements. Extreme heat and flooding can also pose risks to production, with floods leading to hazardous waste spills from mining sites and disruptive and long-lasting damage to electricity and transportation infrastructures.[44] Over half of current lithium mining is in areas with high water stress levels, and risks are exacerbated by climate change as frequency and intensity of extreme weather events increases.

Further risks to supply chains are due to disruptions to freight transport. Blockages and water shortages can create bottlenecks around the Panama and Suez canals and conflicts can create security challenges for international shipping. For example, recent attacks on commercial vessels in the Red Sea have decreased transits through the Suez Canal by an estimated 42%, compared to its historical peak.[48]

Summary of supply chain risks

RISK CATEGORY	RISK	BUYERS	SUPPLIERS	VALUE CHAIN ACTORS
Economic/ financial risks	Trade restrictions	Can have both primarily positive and negative effect on actor	Can have both primarily positive and negative effect on actor	Can have both primarily positive and negative effect on actor
	Price fluctuations	Can have both primarily positive and negative effect on actor	Can have both primarily positive and negative effect on actor	Can have both primarily positive and negative effect on actor
	Supply disruption	Drawback to actor	Drawback to actor	Drawback to actor
	Demand disruption	Drawback to actor	Drawback to actor	Drawback to actor
	Concentrated production/processing	Can have both primarily positive and negative effect on actor	Can have both primarily positive and negative effect on actor	Drawback to actor
	Uncertain mineral availability	Drawback to actor	Drawback to actor	Drawback to actor
Environmental risks	Delayed energy transition	Drawback to actor	Drawback to actor	Drawback to actor
	Local pollution from mining	Does not directly affect actor	Drawback to actor	Drawback to actor
	Soil degradation	Does not directly affect actor	Drawback to actor	Does not directly affect actor
	Water contamination/scarcity	Does not directly affect actor	Drawback to actor	Does not directly affect actor
	Land use change/ biodiversity loss	Drawback to actor	Drawback to actor	Does not directly affect actor
Social risks	Labour exploitation	Does not directly affect actor	Drawback to actor	Drawback to actor
	Public health risks	Does not directly affect actor	Drawback to actor	Drawback to actor
	Indigenous community impact	Does not directly affect actor	Drawback to actor	Drawback to actor
Technological risks	Material substitution	Benefit to actor	Drawback to actor	Can have both primarily positive and negative effect on actor
	Secondary mineral sources	Benefit to actor	Drawback to actor	Can have both primarily positive and negative effect on actor
	Operational failures	Drawback to actor	Drawback to actor	Drawback to actor
External shocks	Natural disasters, conflicts, pandemics.	Drawback to actor	Drawback to actor	Drawback to actor

BENEFIT TO ACTOR — DRAWBACK TO ACTOR — DOES NOT DIRECTLY AFFECT ACTOR — CAN HAVE BOTH PRIMARILY POSITIVE AND NEGATIVE EFFECT ON ACTOR

TABLE 4. SUMMARY OF CMSC RISKS AND THEIR IMPACT.

Policies, Standards, and Global Strategies

KEY TAKEAWAYS

→

There has been a sharp increase in the number of critical mineral policies and international partnerships since 2014, and a further surge since 2019.

→

Governmental policies most often concern security of CMSCs. Other key themes include upholding ESG compliance and domestic ownership of resources.

→

International partnerships and agreements have also been made to enhance the security of the global supply network.

→

Standards to which CMSCs are held, mostly cover traceability and transparency of supply chains and attempt to harmonise reporting standards. Some also cover standards for ESG.

The resilience of CMSCs is key to economic growth and political stability at national, international, and global scales. Since demand for CMs is increasing, and risks on the system are unpredictable , governments and industries enact policies and regulations to minimise the risk posed to their economy. These are in the form of policies, government action plans, international partnerships and agreements, and industry standards. This section catalogues these regulations from around the globe and considers their aims and objectives in maximising CMSC resilience.

International policy landscape of CMSCs

Governmental policies regarding mining and its economics and safety have been in global legislature for decades. Since the importance of certain minerals to the low-carbon energy transition and their scarcity have become clear, policies considering these CMs and their supply chains have been introduced by governments across every continent. This section details an extensive and broad list of these in Table 5, and discusses some key trends and themes between them.

POLICY	COUNTRIES	YEAR	MINERALS	SUMMARY
AFRICA				
Mining Code	DRC	2018	Cobalt, copper, lithium, tantalum, uranium, coltan.	Prime Minister decides on “strategic” minerals. These are taxed at 10% of their value.
Malawi Action Plan for the Open Government Partnership 2023-2025	Malawi	2023	All	Enhances transparency in Malawi's supply chains, addressing issues in contracting and licensing processes, revenue and expenditure disclosure and environmental governance.
Ministerial Regulations No 002/2012/ MINIRENA	Rwanda	2012	Cassiterite, wolframite, coltan, and gold	Designated minerals must be mined, traded, exported and imported in accordance with ICGLR standards.
Mines and Minerals Development Act	Sierra Leone	2022	All	Emphasises transparent and accountable management of the minerals sector in line with international best practices.
ASIA				
"One Belt One Road" Mining Industry Development Fund	China	2015	Gold, silver, copper, lead-zinc, aluminium, iron ore	Invests in high-quality mineral resources along the Silk Road Economic Belt – Kazakhstan, Kyrgyzstan and Tajikistan.
Catalogue of Commodities subject to the Administration of Export Licences	China	2023	Phosphorite, magnesium, rare earths, tin, tungsten, antimony, and germanium	The commodities listed require an export licence.
Mines and Minerals Amendment Act	India	2023	16 including lithium, beryllium, and zirconium	Increase extraction of CMs via exploration licences, governmental power over mineral auctions, and removal of minerals from limited mining list.
Presidential Regulation No. 26/2010	Indonesia	2010	All	Establishes legal basis for the implementation of EITI standards.
Prohibition of the export of nickel ore	Indonesia	2020	Nickel	Ban on the export of nickel ore. Nickel must be processed domestically for export.
Export Ban on Bauxite Ores	Indonesia	2023	Bauxite	Export ban on bauxite ore
Export Benchmark Prices for Mining Products	Indonesia	2024	Gold, iron, lead, zinc.	Set benchmark prices for mining products subject to export duty.
Policy on initiatives for ensuring stable supply of critical minerals	Japan	2023	Lithium, nickel, cobalt, graphite, and manganese	To establish a large battery manufacturing base, subsidies will be given to develop stable foreign CMSCs.
National Mineral Industry Transformation Plan	Malaysia	2021	Rare earth elements, bauxite, tin ore, silica, and kaolin	Strategic framework to develop and streamline the sustainable management of the mineral industry to achieve economic growth.
Mongolia Mineral Law	Mongolia	2014	All	The State is the owner of all subsoil mineral resources and has the right to grant exploration and mining rights.
DENR Administrative Order 2021-40	Philippines	2021	Copper, gold, and silver	Lifted the ban on the open pit method of mining with increased compliance.
EEEV Act	South Korea	2014	Lithium, cobalt, nickel, manganese, and graphite.	Insists on the importance of recycling CMs due to current reliance.
Rare Metals Supply Plan 2.0	South Korea	2021	Rare earths	Ensure security of supply for at least 100 days through acquisitions, stockpiles and recycling.
The strategy for securing reliable critical minerals supply	South Korea	2023	33 critical minerals	Mitigate Korea's reliance on imports from a select few countries by strengthening international cooperation, investment, and risk analysis.
Exploration Enablement Program	Saudi Arabia	2024	Copper, Lithium, Nickel	Aims to grow the domestic CMs mining industry.

POLICY	COUNTRIES	YEAR	MINERALS	SUMMARY
EUROPE				
EU regulation 2017/821	European Union	2021	Gold, tin, tantalum and tungsten	Regulates imports from conflict and high-risk zones.
Critical Raw Materials Act	European Union	2024	All	Ensure EU access to a secure and sustainable supply of CMs to meet 2030 climate objectives.
Earth's Crust Act	Estonia	2016	All	Mineral extraction must have as little adverse impact as possible on the environment, human health, and property.
Decree No. 2022-1550	France	2022	All	Works to identify vulnerabilities linked to the supply of strategic ores and metals
Rare earth elements content disclosure in consumer goods	France	2023	Gold, silver, platinum, palladium, rare earth metals.	Enhance transparency and promote environmentally responsible consumer choices by providing detailed product information.
Raw materials strategy of the Federal Government	Germany	2019	All	Ensure long-term security of supply for raw materials and socially and environmentally fair supply chains.
Supply Chain Act	Germany	2021	All	Strengthens human rights and environmental protection in global supply chains.
Minerals Act	Norway	2010	25 minerals	Regulates permitting, rights, standards and procedures concerning mineral exploration and extraction.
Raw Materials Policy 2050	Poland	2021	All	Ensure resource security by allowing access raw materials (domestic and imported) in the short- and long-term, considering the future.
Royal Decree 647/2002	Spain	2002	29 minerals	Declares certain minerals and their exploration, research, exploitation, use, treatment, and beneficiation as a national priority.
Decree 5/2022	Spain	2022	Lithium	Regulate lithium exploitation such that it benefits locally.
National Minerals Strategy	Sweden	2013	All	Increase competitiveness of mineral mining and ensure resources are used in a sustainable way, considering ecological, social and cultural dimensions.
Eleventh Development Plan	Türkiye	2019	All	Plans to develop CMs exploration projects and regulate strategic reserves and exports.
Resilience for the future: The UK's critical minerals strategy	United Kingdom	2022	Iridium, manganese, nickel, phosphates, ruthenium.	Secure the country's supply chains of CMs by boosting domestic capability
OCEANIA				
Critical Minerals Strategy	Australia	2022	31 critical minerals	Improve access to reliable, secure and resilient supplies of CMs and increase export.
Future Made in Australia Plan	Australia	2024	31 critical minerals	Critical Minerals Production Tax Incentive (AUD 7 billion) and strategic investments in on-going CM projects (AUD 1.2 billion).
Royalty relief for nickel	Australia	2024	Nickel	50% repayable royalty rebate for prices below $US20,000/tonne
Crown Minerals Act	New Zealand	1991	All in territory	Provides the efficient allocation, management and allocation of rights for mining. Amended to shift away from active promotion of mining and toward a more environmentally conscious management of resource.
Minerals and Petroleum Resource Strategy for Aotearoa New Zealand	New Zealand	2019	All	Quantifying mineral resources and identifying which are critical to the well-being of New Zealanders and international partnerships.

POLICY	COUNTRIES	YEAR	MINERALS	SUMMARY
NORTH AMERICA				
Critical Minerals Strategy	Canada	2022	31 critical minerals	To increase the domestic supply of responsibly sourced CMs.
Investment Canada Act	Canada	2022	All	Foreign investments into State-owned CMs enterprises will be tightly controlled.
Self-Government Act	Greenland	2009	All	All revenues from mineral exploitation in subsoil should accrue domestically.
Lithium for Mexico	Mexico	2022	Lithium	National company will control all lithium projects within national territory.
"Strategy to Support Domestic Critical Mineral and Material Supply Chains Materials"	United States	2021	34 critical minerals	To re-establish US competitiveness in CMSCs by: diversifying supply, developing substitutes and improving reuse and recycling.
Trade Act 1974, Section 301	United States	2024	Some	Increase in CMs import tariffs from 0% to 25%.
SOUTH AMERICA				
Law No 928	Bolivia	2017	Lithium	Creation of Bolivian Lithium Deposits for 100% state participation in Lithium supply chains.
Decree 10.657	Brazil	2021	All including niobium, graphite, nickel and rare earths.	Support environmental licensing of investment projects for strategic minerals production.
Mining Royalty Bill	Chile	2023	Lithium and copper	Increased tax on large-scale Li and Cu mining. Royalties dispersed nationally.
National Lithium Strategy	Chile	2023	Lithium	To develop the domestic lithium industry via public-private collaboration.
Article 20 of Law 1753	Columbia	2011	All	Grants the National Mining Authority the right to determine minerals and areas of strategic interest.
Law No 45	Ecuador	2009	All	Aims to correct and prevent the environmental, social and cultural harm that mining may produce.
Law 31.283	Peru	2021	Lithium	Exploration, exploitation and industrialisation of lithium and its derivates are determined as public necessity, national interest, and strategic resources for the country.

TABLE 5. INTERNATIONAL POLICIES REGARDING CRITICAL MINERALS INCLUDING THE COUNTRY OR REGION IN WHICH THEY OPERATE, THE MINERALS WHICH ARE CONSIDERED WITHIN THEM, AND THE YEAR IN WHICH THEY WERE INTRODUCED. TABLES ARE ARRANGED ALPHABETICALLY BY CONTINENT, THEN ALPHABETICALLY BY COUNTRY, THEN CHRONOLOGICALLY BY YEAR. DETAILS AND DATA OF THE LISTED POLICIES FROM THE IEA POLICIES DATABASE.

Globally, policies regarding minerals have evolved over time. Before the turn of the millennium, these policies were mining laws, which dictated variables such as resource ownership and tax. Since 2000, these were joined by policies for increased mineral exploration, social protection, and then environmental protection in the early 2010s. CMs, in the context of the low-carbon energy transition, were not featured in policies in depth until 2002 in the Spanish Royal Decree 975/2009 in which CMs were declared a national priority.[46] End-of-life regulations for technologies containing CMs were introduced from 2010, e.g., the German Electrical and Electronic Equipment Act.[46]

The focus has now shifted towards supply chain security, as seen in policies such as the EU Critical Raw Materials Act (2024) and the U.S. Strategy to Support Domestic Critical Mineral Supply Chains (2021). This focus arose with a ramp up of low-carbon technology, global supply chain disruptions during the COVID-19 pandemic, and an increase in geopolitical unrest in countries with CM resources. Some policies, e.g., Ukraine's Critical Minerals List for Production Sharing Agreements, aim to attract foreign investment, while others, e.g., Mexico's Lithium for Mexico (2022), focus on state control.

The link between CMs and national security has become increasingly explicit, such that some countries include the security of CMSCs within their general security strategies, e.g., Germany's National Security Strategy.[47] Figure 7 shows the countries which had active national minerals strategies from 2018 to 2024 and the year in which the strategy was introduced. Much of Africa, Central Asia, Central America, and Southeast Asia are yet to implement mineral-specific national strategies.

Many nations have developed their own CM lists to guide policy, such as Targeted Critical Minerals and Metals list of South Africa and the Ukraine Critical Minerals List.[46] These lists vary in depth and frequency of updates, affecting their long-term usefulness. Countries have different CMs based on their resources, manufacturing base, and demand for product. Figure 8 shows the frequency at which minerals were declared critical national and international policy lists in 2023. Using these CM lists, countries can identify supply chains which they need to secure.

FIGURE 7

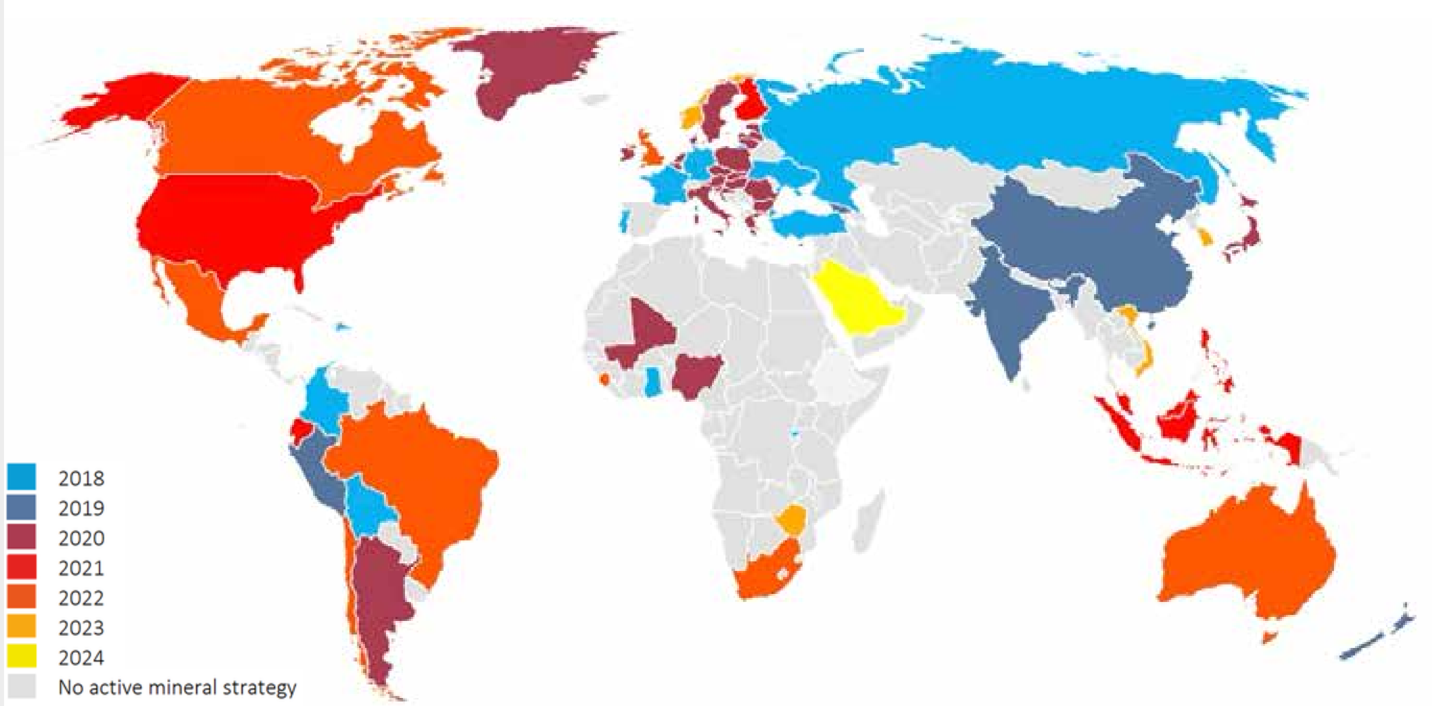


FIGURE 7. COUNTRIES WHICH HAD ACTIVE NATIONAL MINERAL STRATEGIES 2018 – 2024. SOURCES: IEA AND IRENA.[46,48]

Policies mostly do not specify which minerals are included in the policy scope or use their national CMs list. However, some refer specifically to one or a few specific minerals. For example, Bolivia, Chile, Mexico, Spain and Peru have dedicated policies for lithium supply chains, a key mineral to produce Li-ion batteries.

South America has a specific interest in ramping up the exploration and exploitation of lithium reserves, markedly since the COVID-19 pandemic.[49] Since many South American countries possess domestic lithium deposits, mining is of higher importance than security of supply in policies. On the ESG side, there are more policies targeting gender equality within the CMs mining sector than in any other continent, for example, Chile and Columbia's Mining Policies. Other countries have updated their existing human rights policies to include CMSCs, such as Australia's Modern Slavery Act.[50]

Within the EU, policy approach varies by country, depending on domestic resource availability. Norway, with significant resources, has the Norwegian Mineral Strategy, while import-reliant nations including Germany focus on securing external supply chains. France has used monetary funding and tax reliefs in recent years to build secure domestic and foreign CMSCs. As in South America, post-COVID-19 recovery plans in the EU feature the security of supply chains, e.g., Build Back Greener in the UK and the National Plans for Recovery and Resilience in Belgium and Italy.[46]

The US and China are key players in global CMSCs, in both production and consumption. They both have comprehensive sets of policies, spanning mining, processing, trade controls, and recycling. In China, CMs feature in more general policies including the Catalogue for Encouraged Foreign Investment (2022).[46] The US is currently investing heavily in building domestic supply chains, production facilities, battery manufacturing capabilities, and CM recycling plants.

The depth of detail in CM policies directly affects their enforceability and effectiveness in securing supply chains. Policies with a narrow focus, such as Lithium for Mexico (2022), which establishes clear state control over lithium projects, are easier to implement and regulate. In contrast, broader frameworks, for example, Chile's National Lithium Strategy, provide general guidelines but lack the structure for strict enforcement. While highly specific policies ensure better oversight, the complexity of CMSCs means that broader policies are necessary to cover multiple minerals and jurisdictions. **However, if too expansive or vague, policies risk being ineffective, leaving supply chains exposed to geopolitical instability and resource shortages. Overly broad or outdated policies may lack enforceability, leaving supply chains vulnerable to geopolitical risks, market fluctuations, and resource shortages.**

FIGURE 8

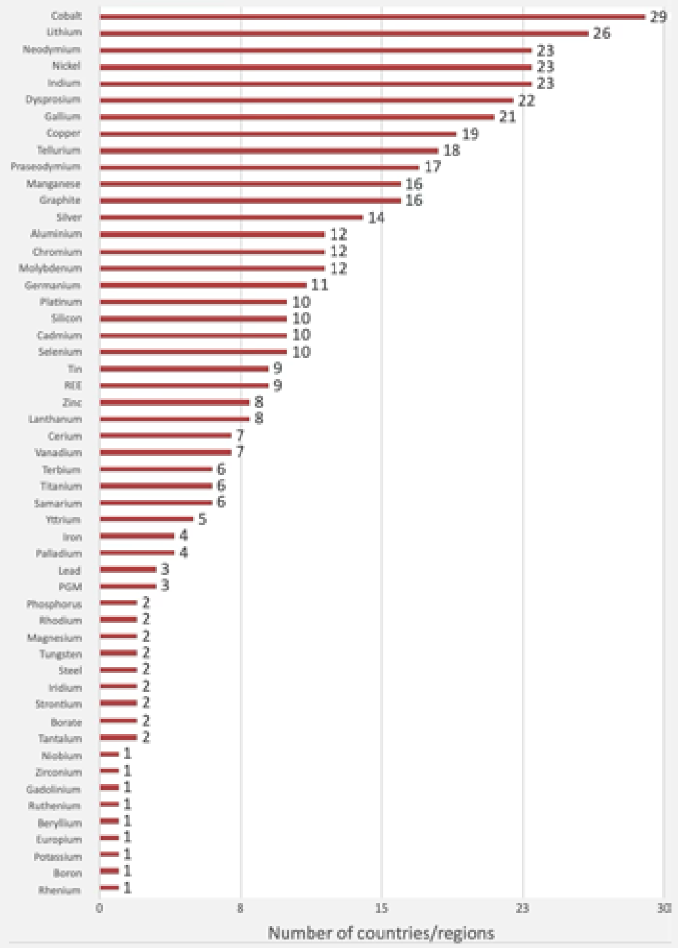


FIGURE 8. MINERALS DEFINED AS CRITICAL BY COUNTRIES AND REGIONS IN 2023.[48]

PARTNERSHIP	COUNTRIES	YEAR	SUMMARY
Bilateral Partnerships with Canada [46]	Canada & Australia, Chile, EU, France, Germany, Indonesia, Italy, Japan, UK and US.	2020 - 2024	Varying collaborations to promote secure and integrated supply chains and improve ESG. CM producers focus on information and standards sharing and those with a manufacturing base focus on strengthening value chains from Canada into their country.
Strategic Partnerships on Raw Materials [46]	EU & Ukraine and Canada	2021	Develop mineral resources and integrating them into global value chains in a socially responsible and sustainable way.
Minerals Security Partnership [51]	Australia, Canada, Finland, France, Germany, Japan, Korea, Sweden, UK, US, & EU	2022	Ensure CMs are produced, processed, and recycled such that the countries realise the full economic development benefit of their mineral resources.
Sustainable Critical Minerals Alliance [52]	Canada, Australia, Germany, France, Japan, UK & US.	2022	Develop sustainable and inclusive mining practices and sourcing CMs which abide by ESG criteria.
Quad Statement of Principles on Clean Energy Supply Chains in the Indo-Pacific [53]	Australia, India, Japan & the United States	2022	Tackle urgent problems in Indo-Pacific CMSCs, including diversification, ESG compliance, and investment encouragement.
Critical Minerals Partnership [46]	Australia & Japan	2022	Establishes a framework to promote opportunities for information sharing and collaboration.
Strategic Partnerships on sustainable raw materials value chains [54]	EU & Argentina, Chile, DRC, Zambia and Namibia	2022 - 2023	Secure strategic and CMs from the country to the EU in a sustainable manner including infrastructure and workforce development, ESG compliance, and research.
Joint Communique on Critical Raw Materials[55]	France, Germany & Italy	2023	Set domestic extraction, processing and recycling targets for each strategic raw material and enforce ESG criteria. Including but not limited to lithium, nickel, rare earth elements, gallium and tungsten.
Strategic Dialogue on Critical Minerals [56]	Australia & France	2023	Joint study to build secure, reliable and sustainable, supply chains both domestic and foreign.
Joint declaration of intent on a critical minerals value chain feasibility study [57]	Australia & Germany	2023	Create new opportunities for Australia to Germany CMs value chains, ensuring ESG standards are met.
Joint Statement of Intent on collaboration on critical minerals [58]	Australia & United Kingdom	2023	Combine Australia's production capacity with the UK's mineral trading and finance expertise to boost global supplies and protect supply chains from shocks.
Climate, Critical Minerals and Clean Energy Transformation Compact [46]	Australia & United States	2023	Share information to coordinate the supply of CMs essential to the global energy transformation, identify risks and market distortions, consider mitigation options, and identify solutions, including standards and investment.
Agreement on Strengthening Critical Minerals Supply Chains [59]	US & Japan	2023	Strengthen and diversify the supply chains of CMs essential for clean energy and EV batteries: cobalt, graphite, lithium, manganese and nickel.

TABLE 6. CURRENT INTERNATIONAL PARTNERSHIPS, AGREEMENTS AND DIALOGUES BETWEEN TWO OR MORE COUNTRIES REGARDING CMSCS. INCLUDING THE COUNTRIES INVOLVED AND YEAR IN WHICH THEY WERE INTRODUCED.

International partnerships in CMSCs

In recent years, governments have increasingly collaborated to secure CMSCs, reflecting the growing importance of these resources in global industries. These partnerships include signed agreements, alliances, working groups, and dialogues that aim to strengthen supply security, promote ESG standards, and increase the economic efficiency of both resource-rich nations and industrial nations.

These partnerships have all been initiated since 2018, with most arising since 2022. This surge is likely driven by multiple factors. Firstly, the global low-carbon energy transition has increased demand for CMs including lithium, copper, nickel, and rare earth elements, which are essential for batteries and other low-carbon technologies. This has drawn governmental and industrial attention to CM security of supply and the strategic importance of their value chains. Simultaneously, increasing global geopolitical tensions and unrest have heightened the urgency of securing diversified and secure supply chains, notably, Russia's War on Ukraine and China's dominance in mineral processing and manufacturing.

These CM partnerships occur largely between developed countries. Markedly, China and Russia do not feature, despite being highly rich in some CM resources and with a high demand for others. Countries seek to reduce reliance on China's processing dominance and Russia's insecure supply chains.[60] African and South American countries are also featured less, with the listed countries seemingly prioritising partnerships with countries with which they have existing economic relationships. [61] Less-developed nations often face increased governance risks and Chinese market influence, making them less attractive for direct agreements. Instead, the featured countries are focussing on de-risking supply chains through trusted allies while maintaining private investments in African and emerging markets. However, there are more governmental partnerships in the pipeline and existing non-governmental CM working relationships between many countries globally, through industry and research partnerships.

Australia and Canada are rich in CM resources and have both formed many partnerships with countries with high demands for CMs, such as Japan and Germany. High-demand countries require the steady import of CMs to operate their manufacturing bases and look for geopolitically-stable countries to import from.

These agreements illustrate a shift towards a more coordinated global approach to securing CMSCs. As well as fostering relationships and projects, these partnerships are an avenue for the development of comprehensive standards for CMSCs, including ESG criteria and its compliance.

PARTNERSHIP	COUNTRIES	YEAR	MINERALS	SUMMARY
GEOGRAPHICALLY-BASED				
Environmental Code of Practice for metal mines [62]	Canada	2009	All	Provides guidance on best practice for environmental management of mines across all mining phases. Covers air, waste, water and biodiversity.
Chinese Due Diligence Guidance for Responsible Mineral Supply Chain [63]	China and OECD	2015	All	Guidelines for extraction and use of minerals to abide by international standards of the OECD.
OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas [64]	OECD countries	2016	All	Recommendations to help companies source minerals responsibly, respect human rights and avoid contributing to conflict. Developed through a multi-stakeholder process with the OECD and ICGLR.
Standard for public reporting of the results of mineral exploration, resources and reserves [46]	Colombia	2018	All	Aims to increase investment in the Colombian mining sector by providing reliable and transparent information focussing on financial, socioeconomic, legal and environmental aspects of mining.
Guidelines for additional environmental measures for operating surface metallic mines [65]	Philippines	2018	Nickel	Sustainable practices for surface metallic mines that covers soil stripping, buffer zones and revegetation. Companies must post a bond they are fined against for every violation of practices.
International Conference on the Great Lakes Region (ICGLR) standards [66]	Angola, Burundi, CAR, Congo, DRC, Kenya, Rwanda, South Sudan, Sudan, Tanzania, Uganda, and Zambia	2019	Tin, Tantalum, Tungsten and Gold	Aims to ensure that mineral supply chains do not support non-state armed groups involved in illegal activities or human rights abuses to promote ethical practices across the supply chain.
Mining (Designated Minerals Certification) Regulations [67]	Tanzania	2019	All	A manual which outlines procedures for tracking mineral products originating from DRC soil from extraction to export.
Ordinance on Due Diligence Obligations and Transparency Regarding Minerals and Metals from Conflict Areas and Child Labour [46]	Swiss companies	2021	All	Mandate on Swiss companies which import or process minerals to file due diligence reports on their supply chain that details risk, human rights, emissions and child labour. Penalties imposed.
Material and Digital Traceability for the Certification of Critical Raw Materials [68]	EU	2022	All	A digital, geochemical, and artificial fingerprinting traceability tools to improve the security and transparency of the CMs supply chain. These tools will then be integrated with a certification scheme to monitor compliance and sustainability.
Final Rules on the clean vehicle provisions of the Inflation Reduction Act [69]	United States	2022	All	Supply chain verification for EV battery components. Requires tracking and supply chain analysis to ensure compliance with non-Foreign Entity of Concern requirements.
Mining Traceability and Transaction Control System [46]	Colombia	2023	All	Comprehensive digital platform to track mineral transactions, verify legal origins, and monitor production volumes across the nation's mining sector.
Regulations on the Management of Rare Earths [46]	China	2024	Rare earth metals	State-controlled and enforced framework for the mining, processing and trade of rare earth materials. Businesses must comply with strict environmental, safety and export controls along with product trackability.
Traceability Procedures Manual for Tradable Mining Products [70]	DRC	2024	All	Guidelines for tracking minerals in the DRC across the entire supply-chain, aligning with CIRGL and OECD standards to improve transparency and prevent exploitation.

PARTNERSHIP	COUNTRIES	YEAR	MINERALS	SUMMARY
MINERALS-BASED				
The International Tin Supply Chain Initiative [71]	Central Africa	2009	Tin, tantalum, and tungsten	Ensure these minerals are not linked to child labour or armed groups using traceability.
Responsible Cobalt Initiative (RCI) [72]	DRC	2016	Cobalt	Aligns company supply chain policies with OECD and Chinese due diligence guidelines to increase transparency and address risks in cobalt supply chains.
Responsible Mica Initiative [73]	India	2016	Mica	Initiative to eliminate child labour using Compliance Self-Assessment and Corrective Action Plan Tools.
ASI Performance Standard [74]	Companies globally	2017	Aluminium	Defines 62 environmental, social and governance principles and criteria to address sustainability issues in the value chain.
The Tin Code [75]	Companies globally	2018	Tin	ESG standards based on a progressive rating system with an expectation of making progressive improvement.
The Risk Readiness Assessment Criteria Guide [76]	Companies globally	2019	All	Promote a common understanding of ESG due diligence requirements, and to enable users to assess and manage risks in mineral supply chains using self-assessment and self-reporting tools.
Sustainable Bauxite Mining Guidelines [77]	Companies globally	2022	Bauxite	Sets out key principles in sustainable bauxite mining operations including health and safety and ESG.
Cobalt Refiner Supply Chain Due Diligence Standard [78]	Companies globally	2022	Cobalt	The standard encourages companies to source responsibly from Conflict-Affected and High-Risk Areas.
The Copper Mark Chain of Custody Standard [79]	Companies globally	2022	Copper	Detailed criteria for copper facilities to increase transparency in primary and secondary copper supply chains.

TABLE 7. INDUSTRY AND CORPORATE STANDARDS FOR CMSCS INCLUDING ESG COMPLIANCE, RESPO7SIBLE SOURCING, AND SUSTAINABILITY INITIATIVES. STANDARDS ARE DIVIDED INTO GEOGRAPHY-BASED AND MINERAL-BASED AND THEN LISTED CHRONOLOGICALLY.

Industry and corporate standards for CMSCs

Alongside government policies and international partnerships, industry-led standards play a crucial role in regulating CMSCs. Governmental bodies and industry groups have developed frameworks for ESG compliance, responsible sourcing, and sustainability initiatives to ensure ethical and sustainable mineral extraction and processing. These standards help mitigate risks such as environmental degradation, human rights violations, and supply chain disruptions, complementing governmental efforts to create a more secure and responsible global CMs industry. This section details an extensive list of these standards in Table 7, and discusses some key themes between them.

Industry standards for CMSCs vary in scope and enforceability, reflecting differences between producing and importing countries, varying mineral resources, and varying governance. Some frameworks, such as the Risk Readiness Assessment Criteria Guide (2019), are voluntary, offering companies a framework to self-assess their supply chain risks. Others, such as Switzerland's Ordinance on Due Diligence (2021), impose legal obligations, requiring businesses to comply with environmental and human rights regulations or face penalties. While voluntary initiatives promote flexibility and industry buy-in, legally binding regulations ensure compliance and accountability, reducing the risk of non-adherence.

A clear distinction emerges between standards in producing countries, which focus on ethical extraction and transparency, and those in importing countries, which emphasize due diligence in sourcing. For example, China's Rare Earths Regulations (2024) strictly control the mining and export of rare earth materials, while Swiss standards mandate due diligence reports on all imports. Producing nations including the DRC, Tanzania, and Colombia have introduced traceability mechanisms to certify minerals as legally and ethically sourced. These frameworks aim to curb illicit mining, child labour, and environmental harm, but their effectiveness often depends on enforcement capacity.

Across the standards in Table 7, common themes include ESG compliance, traceability, responsible sourcing, and risk mitigation. ESG standards are crucial in addressing ethical concerns, but their impact depends on enforcement, industry commitment, and global alignment. While legally binding regulations provide stronger safeguards, voluntary standards encourage broader participation and innovation in sustainable mining practices. A hybrid approach, combining government mandates with industry-driven compliance, appears to be the most effective in securing responsible CMSCs.

Recommendations

Reviewing the literature on CMSCs over the last decade reveals that most studies concentrate on the supply side (mining), with fewer addressing downstream value chain vulnerabilities and demand-side factors. Future research and policy efforts should prioritise a more comprehensive analysis of downstream vulnerabilities, including processing/refining efficiency, advanced manufacturing technology, recycling, and end-use demand fluctuations to address this imbalance. This broader scope will help identify bottlenecks that influence supply chain stability.

The disruptions analysed – specifically geopolitical and policy-related risks and resource/reserve scarcity – are among the most pressing concerns. Therefore, governments and industry actors should develop integrated risk monitoring systems that not only track geopolitical and policy developments but also proactively assess underexplored threats, such as environmental and climate-induced disruptions, as well as operational and technological risks, such as machinery failure.

Despite growing awareness of these risks, much of the literature has focused on individual minerals, specific regions, or isolated mitigation techniques. To support effective strategic planning, future studies and government assessments should adopt an integrated, system-level perspective, capturing the interdependencies between different stages of the supply chain and their links to broader socio-economic and environmental systems. This approach is vital for building resilient CMSCs capable of withstanding market volatility, accelerating technological transitions, and responding to global sustainability imperatives.

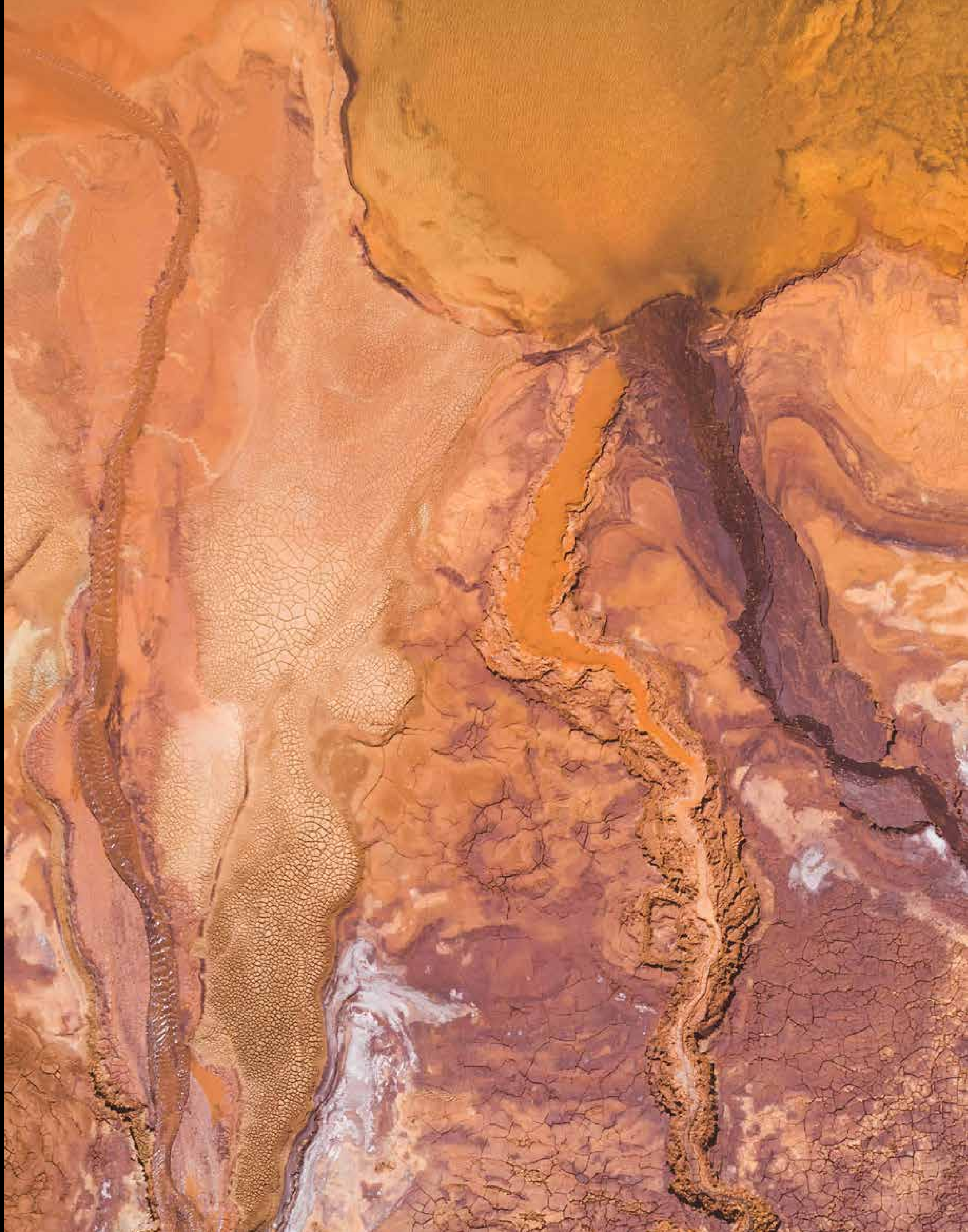
Conclusion

Recent studies emphasise that a resilient supply chain is crucial to adapt to and recover from disruptions, ensuring a continuous supply of CMs needed for technological innovation and sustainable development. As demand for these CMs continues to rise, vulnerabilities across the global supply chain have become more pronounced, revealing structural risks at every supply chain stage.

This report has demonstrated that supply-side risks, such as concentrated production and limited processing capacities, are intensified by external disruptions such as geopolitical conflict, trade restrictions, and environmental pressures. The differentiated risk exposure across upstream, midstream, and downstream actors underscores the need for tailored mitigation measures that account for economic, technological, environmental, and social dimensions.

While diversification remains the dominant mitigation approach, strategies such as investment in recycling and material substitution present significant opportunities to increase resilience across the CMSCs. Moreover, multilateral cooperation, harmonised policy frameworks, and transparent market mechanisms are essential to facilitate sustainable and equitable access to critical resources.

Enhancing supply chain resilience requires coordinated action among governments, industry stakeholders, and researchers. A practical approach will be vital to ensure CMSCs can support long-term technological, economic, and environmental fluctuations.



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PLEASE CITE AS: HEYDARI M, JENNINGS ET, THOMAS H, CABRERA SERRENHO A, CULLEN JM (2025) RESILIENCE OF CRITICAL MINERAL SUPPLY CHAINS. UNIVERSITY OF CAMBRIDGE.

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RESEARCH IN THIS REPORT IS FUNDED BY CCG, CLIMATE COMPATIBLE GROWTH: HTTPS://CLIMATECOMPATIBLEGROWTH.COM/ABOUT-US/

UNIVERSITY OF CAMBRIDGE

WHO WE ARE

CAMBRIDGE CRITICAL MATERIALS LAB

We believe the energy transition must be equitable and inclusive. That means mineral-rich countries and their communities should benefit fully from their resources. By co-creating information platforms, producing rigorous research, and building tools for better decision-making, we work to strengthen equity in how critical materials are used to ensure no one is left behind.

CAMBRIDGECRITICALMATERIALS.LAB

HOW WE WORK

We combine independent, interdisciplinary research with close collaboration across the Global South to ensure mineral governance is technically sound, socially just, and climate-compatible. By integrating engineering, policy, and social sciences, we create actionable insights that empower governments and communities to defend their rights, advance their interests, and navigate the complex environmental, social, and economic challenges of the energy transition.

OUR TEAM

Blending engineering, policy, and social sciences, our team finds innovative solutions to complex challenges.