Resources Policy
**Date:** October 2026
**Article:** 106039
**Volume:** Volume 121
**Published by:** Elsevier
Show less

Research article Get rights and content

# Mapping the global nickel ore trade networks and the competitiveness of nickel-exporting countries

Reninta Dewi Nugraheni [a], Iwan Hermawan [a], Carunia Mulya Firdausy [b], Shiddiq Sugiono [c] Show more



10.1016/j.resourpol.2026.106039



## Highlights

- Global nickel trade is driven more by consumer than producer countries.
- China, Germany, and the USA dominate the global nickel trade network.
- Nickel trade patterns reveal strong dependence on major consumer countries.
- Supply-chain diversification can reduce reliance on single import sources.
- Geopolitical risk requires market diversification and stronger strategic alliances.



## Abstract

This study aimed to map the global nickel ore trade networks and the competitiveness of nickel-exporting countries. Trade Map data for nickel ores and concentrates under Harmonized System (HS) 2604 for 2012-2023 were analysed using social network analysis, revealed comparative advantage, revealed symmetric comparative advantage, Spearman's rank correlation, and an integrated Social Network Analysis-Revealed Symmetric Comparative Advantage (SNA-RSCA) classification. The results show that the network remained concentrated around a limited number of highly connected economies despite changes in bilateral links and community membership. China maintained the most prominent demand-oriented position through high trade intensity, broad supplier connectivity, brokerage potential, and network accessibility. RSCA is positively associated with strength and out-degree, whereas its relationships with in-degree, betweenness, and closeness are weak and statistically insignificant. Nickel ore export advantage is therefore closely associated with trade intensity and destination reach rather than with import connectivity or intermediary position. The SNA-RSCA typology distinguishes high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries. Movement across these categories shows that structural prominence and revealed ore-export advantage may evolve independently, particularly when industrial policy redirects raw-ore trade toward domestic processing. The findings demonstrate that resource endowment, network centrality, and export competitiveness are distinct but related dimensions and provide a diagnostic basis for differentiated policies on trade, supply security, and market diversification.

## Keywords

Nickel ore trade; Social network analysis; Revealed comparative advantage; Network position; Export competitiveness

Previous article in this issue

Next article in this issue

## Introduction

Nickel has become increasingly strategic to the global economy because of its importance for stainless steel production, industrial applications, and low-carbon technologies. Growing demand, geographical concentration of mineral resources, export restrictions, geopolitical tensions, and supply-chain disruptions have intensified concerns regarding the stability of international nickel trade (Mudd and Jowitt, 2022; Jia et al., 2024; Basuhi et al., 2024). These developments have encouraged countries to strengthen supply security, diversify trade relationships, and expand domestic processing capacity.

Within the broader nickel economy, nickel ores and concentrates constitute a distinct upstream trade segment. Nickel ore trade directly links resource-producing countries with economies possessing processing capacity and industrial demand. Its structure therefore differs from that of refined nickel, intermediate nickel products, and downstream battery or stainless-steel materials. This distinction is important because evidence concerning the entire nickel industry chain cannot automatically be interpreted as evidence of competitiveness in nickel ore trade.

Nickel reserves and production are geographically concentrated, whereas processing capacity and industrial demand are concentrated in a different group of countries. Indonesia and Australia possess substantial nickel reserves, followed by Brazil and the Philippines, while China has a relatively limited domestic resource base (USGS, 2022). Nevertheless, China occupies an influential position in the international nickel economy because of its great industrial demand, processing capacity, and diversified supply relationships. This asymmetry indicates that resource ownership alone does not determine a country's strategic position. Market access, trade connectivity, processing capacity, and dependence on major partners also shape countries' roles within the nickel ore trade network.

Indonesia illustrates how industrial policy can reconfigure upstream trade relationships. Its nickel ore export restrictions were introduced to encourage domestic processing, reduce reliance on raw-material exports, and strengthen value capture within the national nickel industry (Patunru, 2023; Warburton, 2024). These measures reduced Indonesia's direct participation in Harmonized System (HS) 2604 exports and redirected demand toward alternative suppliers, particularly the Philippines. From a network perspective, such policy intervention can remove established links, reshape buyer–supplier relations, and alter bargaining opportunities among producing and importing countries. It may therefore change a country's position in the ore-trade network even when the broader objective is to improve its role in downstream segments of the value chain.

Previous studies have generated important insights into the global nickel economy. Research has examined physical and monetary nickel flows, structural differentiation along the nickel product chain, country risk, supply-chain vulnerability, crisis propagation, and price transmission (Zheng et al., 2022; Jia et al., 2024; Chen et al., 2024; Sun et al., 2024). These studies show that nickel trade is characterised by concentration, core-periphery relations, unequal value capture, and dependence on a limited number of major producing and consuming economies. However, many of these studies cover multiple nickel products or the broader nickel industry chain rather than focusing specifically on ores and concentrates.

A smaller group of studies has examined the nickel ore trade network more directly. Ding (2020) investigated the evolution of international nickel ore trade, Dong et al. (2021) examined network optimization, Yang et al. (2021) identified potential new trade relationships, and Wang et al. (2022) and Yu et al. (2023) assessed network stability and resilience. These studies successfully identified central countries, vulnerable relationships, structural concentration, and the effects of supply disruption. However, their primary emphasis is the structure and functioning of the trade network rather than countries' revealed export competitiveness.

Social Network Analysis (SNA) measures countries' relational positions through indicators such as degree, strength, betweenness, and closeness centrality. These measures capture connectivity, trade intensity, market reach, accessibility, and brokerage potential (Gönçer-Demiral and İnce-Yenilmez, 2022). Within this study, these structural properties are interpreted as indicators of market access, dependency exposure, and bargaining or brokerage capacity. Nevertheless, centrality does not directly measure comparative advantage and should not automatically be treated as evidence of competitiveness. A country may occupy a central position because it is a major importer or intermediary, even when it does not possess revealed comparative advantage in nickel ore exports.

Conversely, Revealed Comparative Advantage (RCA) and Revealed Symmetric Comparative Advantage (RSCA) measure product-specific export specialization relative to national and global export structures. Studies using RCA can identify whether a country possesses a revealed advantage in nickel exports, including changes associated with export restrictions (Suryanto, 2022). However, RCA/RSCA do not show whether that advantage is supported by diversified market access, embeddedness in major trade communities, or reduced dependence on dominant buyers. A country may therefore have strong nickel ore export specialization while remaining structurally peripheral and vulnerable to demand changes in one or a few markets.

This difference defines the central research gap. Network position and revealed export competitiveness are related but non-equivalent dimensions shaped by countries' value-chain roles and industrial-policy choices. Processing and demand hubs may occupy influential network positions without specialising in ore exports, while resource-producing countries may retain strong ore-export specialization but remain dependent on a limited number of downstream markets. Existing studies generally examine either network structure and disruption or revealed export competitiveness. Limited attention has been given to how network position, dependency, value-chain role, and nickel ore export competitiveness intersect within a single framework.

This study, therefore, develops an integrated framework explaining how network structure shapes strategic competitiveness in critical mineral markets. Rather than treating network centrality as a descriptive topological property, we conceptualise it as a structural governance mechanism through which countries gain market power, manage dependency, and reposition themselves within global value chains during the energy transition. This perspective shifts the analysis from describing trade patterns to explaining why countries with abundant mineral resources do not necessarily achieve stronger strategic competitiveness.

Building on this framework, the study maps the evolution of the global nickel ore trade network (HS 2604) during 2012–2023 and examines how countries' structural positions relate to revealed export competitiveness under changing industrial-policy and geopolitical conditions. By jointly analysing Social Network Analysis (SNA) and RCA/RSCA indicators, the study demonstrates that network influence and export competitiveness represent distinct but interdependent dimensions of strategic performance. Countries may occupy central positions because of demand, processing capacity, brokerage, or market connectivity without possessing comparative advantage in ore exports, while resource-rich exporters may exhibit strong comparative advantage yet remain structurally dependent on dominant processing hubs.

Accordingly, the study advances the literature in three respects. First, it provides a theoretical reinterpretation of network centrality as an indicator of governance, bargaining power, dependency, and value-chain positioning rather than merely trade connectivity. Second, it develops an integrated SNA–RCA/RSCA diagnostic framework that distinguishes structural influence from revealed competitiveness and identifies four strategic country configurations: high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries, thereby offering a more nuanced explanation of competitive positioning in critical mineral trade. Third, by focusing specifically on upstream nickel ore (HS 2604), the study reveals how downstream industrial policies and value-chain upgrading reshape trade-network positions and export competitiveness, providing a conceptual bridge between trade-network analysis, global value chain upgrading, and critical mineral governance.



## Section snippets

### Literature review

Nickel's strategic role in the global energy transition has increased interest in mineral trade, critical-mineral supply chains, resilience, and policy intervention. Much of this literature examines the broader nickel industry, including refined nickel, intermediate products, stainless steel, battery materials, and recycling. These studies provide important context but cannot be treated as direct evidence of competitiveness in nickel ores and concentrates. This study therefore focuses on HS …

### Data source

This study used international nickel ore trade data (HS code 2604) obtained from the Trade Map database for the period 2012–2023, with country classifications based on the database nomenclature. The network includes all importers during the study period. Although export and import statistics are theoretically equivalent, reporting discrepancies frequently arise. Following prior studies (Shi et al., 2021; Zeng et al., 2018), this study used import data, which are generally more reliable due to …

## The global nickel ore trade network

Fig. 1 shows that nickel mine production and reserves are concentrated in a limited number of countries, particularly Indonesia, the Philippines, and New Caledonia. This upstream concentration underscores the importance of resource-rich countries in determining the physical availability of nickel ore, although resource ownership does not automatically translate into a central network position or revealed nickel ore export competitiveness. Meanwhile, China dominates nickel ore imports with an …

## Conclusions

This study examined how the structure of the global nickel ore trade network evolved between 2012 and 2023 and whether countries' network positions corresponded with their revealed export competitiveness. By combining social network analysis with RCA/RSCA, it demonstrates that prominence in the HS 2604 trade network and specialization in nickel ore exports represent distinct dimensions of international trade performance. A country may occupy an important structural position because of its …

## Policy implications

The findings suggest that nickel ore policy should be considered within the broader value chain rather than based on HS 2604 trade performance alone. Ore demand is shaped by processing capacity, industrial investment, technological requirements, and downstream demand from stainless-steel and battery-related industries. A country's network position therefore reflects not only resource endowment and market access but also the location and development of processing activities.

The SNA-RSCA matrix …

## CRediT authorship contribution statement

**Reninta Dewi Nugraheni:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Iwan Hermawan:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Carunia Mulya Firdausy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Shiddiq Sugiono:** …

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. …

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

## Acknowledgements

We gratefully acknowledge the anonymous editor and the two anonymous reviewers for their insightful comments and constructive suggestions, which helped us significantly improve the quality of this manuscript. Any remaining errors are ours. …

## References (37)

R. Basuhi *et al.*

Clean energy demand must secure a sustainable nickel supply

Joule (2024)

A. Coveri *et al.*
Global value chains and within-country inequality: the role of functional positioning
Struct. Change Econ. Dynam. (2024)

X. Dong *et al.*
Optimization of the international nickel ore trade network
Resour. Policy (2021)

S. Dou *et al.*
The power of mineral: shock of the global supply chain from resource nationalism
World Dev. (2024)

Y. Fan *et al.*
The state's role and position in international trade: a complex network perspective
Econ. Modell. (2014)

S.B. Khalil *et al.*
Stainless success, battery lag: evaluation of Indonesia's resource nationalism in nickel
Extr. Ind. Soc. (2025)

A. Kocourek
Structural changes in comparative advantages of the BRICS
Proced. Soc. Behav. Sci. (2015)

Y. Ma *et al.*
Analysis of the characteristics and stability of the global complex nickel ore trade network
Resour. Policy (2022)

J. Shi *et al.*
The expansion and shrinkage of the international trade network of plastic wastes affected by China's waste management policies
Sustain. Prod. Consum. (2021)

X. Sun *et al.*
Physical and monetary characterization of the global nickel flow network
Resour. Policy (2024)

E. Warburton
Nationalist enclaves: industrialising the critical mineral boom in Indonesia
Extr. Ind. Soc. (2024)

Y. Yu *et al.*
A resilience measure for the international nickel trade network
Resour. Policy (2023)

X. Zeng *et al.*
Examining the sustainability of China's nickel supply: 1950–2050
Resour. Conserv. Recycl. (2018)

S. Zheng *et al.*
Impact of countries' role on trade prices from a nickel chain perspective: based on complex network and panel regression analysis
Resour. Policy (2022)

B. Balassa
Trade liberalisation and revealed comparative advantage
Manch. Sch. (1965)

W. Chen *et al.*
Unveiling structural differentiation in the global nickel trade network: a product chain perspective
J. Geogr. Sci. (2024)

I. Cingolani *et al.*
Countries' positions in the international global value networks: centrality and economic performance
Appl.Network Sci. (2017)

A. Coveri *et al.*
The virtues and limits of specialization in global value chains: analysis and policy implications
J.Industrial Bus. Econ. (2023)

There are more references available in the full text version of this article.

View full text

## Recommended articles

No articles found.

Resources Policy 121 (2026) 106039

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

# Mapping the global nickel ore trade networks and the competitiveness of nickel-exporting countries

Reninta Dewi Nugraheni [a], Iwan Hermawan [a], Carunia Mulya Firdausy [b,*], Shiddiq Sugiono [c]

[a] Research Centre for Industrial Economics, Services and Trade - National Research and Innovation Agency, Jakarta, Indonesia
[b] Research Centre for Industrial Economics, Services, and Trade - National Research and Innovation Agency and, Faculty of Economics and Business, Universitas Tarumanagara, Jakarta, Indonesia
[c] Measurement and Indicators for Research Technology and Innovation, National Research and Innovation Agency, Jakarta, Indonesia

ARTICLE INFO

*Keywords:*
Nickel ore trade
Social network analysis
Revealed comparative advantage
Network position
Export competitiveness

ABSTRACT

This study aimed to map the global nickel ore trade networks and the competitiveness of nickel-exporting countries. Trade Map data for nickel ores and concentrates under Harmonized System (HS) 2604 for 2012-2023 were analysed using social network analysis, revealed comparative advantage, revealed symmetric comparative advantage, Spearman's rank correlation, and an integrated Social Network Analysis-Revealed Symmetric Comparative Advantage (SNA-RSCA) classification. The results show that the network remained concentrated around a limited number of highly connected economies despite changes in bilateral links and community membership. China maintained the most prominent demand-oriented position through high trade intensity, broad supplier connectivity, brokerage potential, and network accessibility. RSCA is positively associated with strength and out-degree, whereas its relationships with in-degree, betweenness, and closeness are weak and statistically insignificant. Nickel ore export advantage is therefore closely associated with trade intensity and destination reach rather than with import connectivity or intermediary position. The SNA-RSCA typology distinguishes high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries. Movement across these categories shows that structural prominence and revealed ore-export advantage may evolve independently, particularly when industrial policy redirects raw-ore trade toward domestic processing. The findings demonstrate that resource endowment, network centrality, and export competitiveness are distinct but related dimensions and provide a diagnostic basis for differentiated policies on trade, supply security, and market diversification.

## 1. Introduction

Nickel has become increasingly strategic to the global economy because of its importance for stainless steel production, industrial applications, and low-carbon technologies. Growing demand, geographical concentration of mineral resources, export restrictions, geopolitical tensions, and supply-chain disruptions have intensified concerns regarding the stability of international nickel trade (Mudd and Jowitt, 2022; Jia et al., 2024; Basuhi et al., 2024). These developments have encouraged countries to strengthen supply security, diversify trade relationships, and expand domestic processing capacity.

Within the broader nickel economy, nickel ores and concentrates constitute a distinct upstream trade segment. Nickel ore trade directly links resource-producing countries with economies possessing processing capacity and industrial demand. Its structure therefore differs from that of refined nickel, intermediate nickel products, and downstream battery or stainless-steel materials. This distinction is important because evidence concerning the entire nickel industry chain cannot automatically be interpreted as evidence of competitiveness in nickel ore trade.

Nickel reserves and production are geographically concentrated, whereas processing capacity and industrial demand are concentrated in a different group of countries. Indonesia and Australia possess

* Corresponding author.
*E-mail addresses:* reni005@brin.go.id (R.D. Nugraheni), nawih09@gmail.com (I. Hermawan), cmfirdausy@gmail.com (C.M. Firdausy), shid002@brin.go.id (S. Sugiono).

https://doi.org/10.1016/j.resourpol.2026.106039
Received 10 February 2026; Received in revised form 22 August 2026; Accepted 23 August 2026

substantial nickel reserves, followed by Brazil and the Philippines, while China has a relatively limited domestic resource base (USGS, 2022). Nevertheless, China occupies an influential position in the international nickel economy because of its great industrial demand, processing capacity, and diversified supply relationships. This asymmetry indicates that resource ownership alone does not determine a country's strategic position. Market access, trade connectivity, processing capacity, and dependence on major partners also shape countries' roles within the nickel ore trade network.

Indonesia illustrates how industrial policy can reconfigure upstream trade relationships. Its nickel ore export restrictions were introduced to encourage domestic processing, reduce reliance on raw-material exports, and strengthen value capture within the national nickel industry (Patunru, 2023; Warburton, 2024). These measures reduced Indonesia's direct participation in Harmonized System (HS) 2604 exports and redirected demand toward alternative suppliers, particularly the Philippines. From a network perspective, such policy intervention can remove established links, reshape buyer–supplier relations, and alter bargaining opportunities among producing and importing countries. It may therefore change a country's position in the ore-trade network even when the broader objective is to improve its role in downstream segments of the value chain.

Previous studies have generated important insights into the global nickel economy. Research has examined physical and monetary nickel flows, structural differentiation along the nickel product chain, country risk, supply-chain vulnerability, crisis propagation, and price transmission (Zheng et al., 2022; Jia et al., 2024; Chen et al., 2024; Sun et al., 2024). These studies show that nickel trade is characterised by concentration, core-periphery relations, unequal value capture, and dependence on a limited number of major producing and consuming economies. However, many of these studies cover multiple nickel products or the broader nickel industry chain rather than focusing specifically on ores and concentrates.

A smaller group of studies has examined the nickel ore trade network more directly. Ding (2020) investigated the evolution of international nickel ore trade, Dong et al. (2021) examined network optimization, Yang et al. (2021) identified potential new trade relationships, and Wang et al. (2022) and Yu et al. (2023) assessed network stability and resilience. These studies successfully identified central countries, vulnerable relationships, structural concentration, and the effects of supply disruption. However, their primary emphasis is the structure and functioning of the trade network rather than countries' revealed export competitiveness.

Social Network Analysis (SNA) measures countries' relational positions through indicators such as degree, strength, betweenness, and closeness centrality. These measures capture connectivity, trade intensity, market reach, accessibility, and brokerage potential (Göncer-Demiral and İnce-Yenilmez, 2022). Within this study, these structural properties are interpreted as indicators of market access, dependency exposure, and bargaining or brokerage capacity. Nevertheless, centrality does not directly measure comparative advantage and should not automatically be treated as evidence of competitiveness. A country may occupy a central position because it is a major importer or intermediary, even when it does not possess revealed comparative advantage in nickel ore exports.

Conversely, Revealed Comparative Advantage (RCA) and Revealed Symmetric Comparative Advantage (RSCA) measure product-specific export specialization relative to national and global export structures. Studies using RCA can identify whether a country possesses a revealed advantage in nickel exports, including changes associated with export restrictions (Suryanto, 2022). However, RCA/RSCA do not show whether that advantage is supported by diversified market access, embeddedness in major trade communities, or reduced dependence on dominant buyers. A country may therefore have strong nickel ore export specialization while remaining structurally peripheral and vulnerable to demand changes in one or a few markets.

This difference defines the central research gap. Network position and revealed export competitiveness are related but non-equivalent dimensions shaped by countries' value-chain roles and industrial-policy choices. Processing and demand hubs may occupy influential network positions without specialising in ore exports, while resource-producing countries may retain strong ore-export specialization but remain dependent on a limited number of downstream markets. Existing studies generally examine either network structure and disruption or revealed export competitiveness. Limited attention has been given to how network position, dependency, value-chain role, and nickel ore export competitiveness intersect within a single framework.

This study, therefore, develops an integrated framework explaining how network structure shapes strategic competitiveness in critical mineral markets. Rather than treating network centrality as a descriptive topological property, we conceptualise it as a structural governance mechanism through which countries gain market power, manage dependency, and reposition themselves within global value chains during the energy transition. This perspective shifts the analysis from describing trade patterns to explaining why countries with abundant mineral resources do not necessarily achieve stronger strategic competitiveness.

Building on this framework, the study maps the evolution of the global nickel ore trade network (HS 2604) during 2012–2023 and examines how countries' structural positions relate to revealed export competitiveness under changing industrial-policy and geopolitical conditions. By jointly analysing Social Network Analysis (SNA) and RCA/RSCA indicators, the study demonstrates that network influence and export competitiveness represent distinct but interdependent dimensions of strategic performance. Countries may occupy central positions because of demand, processing capacity, brokerage, or market connectivity without possessing comparative advantage in ore exports, while resource-rich exporters may exhibit strong comparative advantage yet remain structurally dependent on dominant processing hubs.

Accordingly, the study advances the literature in three respects. First, it provides a theoretical reinterpretation of network centrality as an indicator of governance, bargaining power, dependency, and value-chain positioning rather than merely trade connectivity. Second, it develops an integrated SNA–RCA/RSCA diagnostic framework that distinguishes structural influence from revealed competitiveness and identifies four strategic country configurations: high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries, thereby offering a more nuanced explanation of competitive positioning in critical mineral trade. Third, by focusing specifically on upstream nickel ore (HS 2604), the study reveals how downstream industrial policies and value-chain upgrading reshape trade-network positions and export competitiveness, providing a conceptual bridge between trade-network analysis, global value chain upgrading, and critical mineral governance.

## 2. Literature review

Nickel's strategic role in the global energy transition has increased interest in mineral trade, critical-mineral supply chains, resilience, and policy intervention. Much of this literature examines the broader nickel industry, including refined nickel, intermediate products, stainless steel, battery materials, and recycling. These studies provide important context but cannot be treated as direct evidence of competitiveness in nickel ores and concentrates. This study therefore focuses on HS 2604 while using the broader nickel value chain to interpret the structural setting of ore trade.

From a global value-chain perspective, resource ownership alone does not determine a country's economic or strategic position. Countries engaged in refining, processing, component production, and manufacturing generally capture more value and develop stronger industrial capabilities than those concentrated in raw-material extraction

(Coveri et al., 2024; Coveri and Zanfei, 2023). Strong mineral endowments and ore-export specialization therefore do not necessarily provide control over processing, pricing, or downstream value creation. Conversely, countries with limited ore resources may become influential through processing capacity, industrial demand, and access to major markets.

Studies of the broader nickel chain describe a concentrated and hierarchical structure with unequal distributions of physical flows, monetary benefits, and industrial capabilities (Zheng et al., 2022; Chen et al., 2024; Sun et al., 2024). Processing and consuming countries may influence trade allocation and value capture, while many resource-rich exporters remain concentrated in upstream activities. These findings help explain the wider context of nickel ore trade, but they do not directly measure HS 2604 competitiveness.

Ore-specific research has focused mainly on network evolution, stability, optimization, and the formation of trade relationships. Ding (2020) examined the development of the international nickel ore network, Dong et al. (2021) assessed its optimization, Ma et al. (2022) analysed structural characteristics and stability risks, and Yang et al. (2021) identified potential new trade links. This literature demonstrates that nickel ore trade is concentrated around key producing and importing countries and that disruptions to central actors can redirect trade. Its primary concern, however, remains network structure and resilience rather than revealed export competitiveness.

This value-chain structure is closely connected to industrial policy. Resource-rich countries increasingly employ export restrictions, domestic-processing requirements, and investment incentives to capture more value from mineral extraction. These measures may support upgrading but can also create trade disputes, investment dependence, environmental pressures, and technological constraints (Warburton, 2024; Dou et al., 2024; Khalil and Broughel, 2025). Indonesia illustrates this process. Its nickel ore restrictions and domestic-smelting requirements reduced participation in raw-ore exports while encouraging processing and redirecting import demand toward alternative suppliers, including the Philippines and New Caledonia.

Industrial policy is not estimated as an independent causal determinant in this study. It is used to interpret changes in network position and RCA/RSCA during 2012–2023. A decline in nickel ore RCA following an export restriction may represent a deliberate shift from raw-ore exports toward domestic processing rather than weaker competitiveness across the wider nickel industry.

A network perspective complements this analysis by examining how power and dependency are shaped by relationships among countries rather than by resource endowments or export values alone (Kali and Reyes, 2007; Cingolani et al., 2017). Central countries may have broader access to suppliers or buyers, more diversified relationships, and greater brokerage potential (Tajoli et al., 2021). Out-degree captures destination reach, in-degree supplier connectivity, trade intensity, betweenness brokerage potential, and closeness relative accessibility. These indicators identify different structural roles and do not directly measure comparative advantage (Gönçer-Demiral and İnce-Yenilmez, 2022).

This distinction is important because importing or intermediary countries may occupy central positions without possessing revealed comparative advantage in nickel ore exports. RCA/RSCA, by contrast, measure whether nickel ore has a relatively important place in a country's export structure. They do not capture market diversification, community membership, or dependence on a small number of buyers. Evidence from Indonesia, for example, suggests that restrictions on raw nickel exports may reduce measured ore-export advantage while domestic processing expands (Suryanto, 2022).

SNA and RCA/RSCA therefore represent related but non-equivalent dimensions. SNA identifies structural position, connectivity, and market access, whereas RCA/RSCA measures revealed nickel ore export specialization. Their integration distinguishes central countries without ore-export advantage from resource-competitive exporters with limited network reach.

Resource dependence further depends on the concentration of trade relationships. Countries relying on one or a few partners are more exposed to changes in demand, trade restrictions, and geopolitical shocks, while diversified relationships may provide greater flexibility (Fan et al., 2014; Xia et al., 2018). A large number of links does not necessarily eliminate dependency, however, because trade value may remain concentrated in a dominant partner.

The resulting framework links four elements. GVC position distinguishes upstream resource specialization from downstream industrial capability; industrial policy helps explain changes in ore-trade participation; SNA captures connectivity, accessibility, brokerage, and trade intensity; and RCA/RSCA measures revealed nickel ore export specialization. Their integration classifies countries as high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries. The study examined convergence and divergence between these dimensions without assuming that network centrality causes export competitiveness.

## 3. Data and methods

### 3.1. Data source

This study used international nickel ore trade data (HS code 2604) obtained from the Trade Map database for the period 2012–2023, with country classifications based on the database nomenclature. The network includes all importers during the study period. Although export and import statistics are theoretically equivalent, reporting discrepancies frequently arise. Following prior studies (Shi et al., 2021; Zeng et al., 2018), this study used import data, which are generally more reliable due to stricter customs controls and reporting standards.

### 3.2. Social network analysis (SNA)

To examine the global nickel ore trade network, this study applied Social Network Analysis (SNA), where countries are represented as nodes and trade flows as directed edges (Seok and Nam, 2022). The network is modelled as directed to capture the directional nature of international trade, where each edge points from an exporting country to an importing country. This representation allows the analysis to identify countries with a high concentration of incoming trade links, indicating their role as major importers in the global nickel ore trade network. The network is constructed using an adjacency matrix $A^{(N)}$, where each entry $a_{ij}$ denotes exports from country $i$ to country $j$, excluding domestic trade (Sajedianfard et al., 2021) as follows.

$$A^{(N)} = \begin{pmatrix} a_{11} & \cdots & a_{1p} & a_{1,p+1} & \cdots & a_{1N} \\ a_{21} & \cdots & a_{2p} & a_{2,p+1} & \cdots & a_{2N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{p1} & \cdots & a_{pp} & a_{p,p+1} & \cdots & a_{pN} \\ a_{p+1,1} & \cdots & a_{p+1,p} & a_{p+1,p+1} & \cdots & a_{p+1,N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{N1} & \cdots & a_{Np} & a_{N,P+1} & \cdots & a_{NN} \end{pmatrix} \tag{1}$$

Trade flows with zero values were excluded from the network because they do not represent an active trade relationship. No additional minimum trade-value threshold was applied. Therefore, all positive trade relationships, including relatively small trade flows, were retained in the analysis. The network was subsequently analysed as an unweighted network, where the existence of a trade relationship rather than its monetary value determined edge formation.

Network structure captures not only trade connectivity but also differences in market access, dependency, and brokerage potential across countries. More central countries may have broader trade relationships and greater structural flexibility, but centrality does not automatically translate into resilience or export competitiveness. In this study, it is therefore treated as a structural condition that may be associated with competitiveness rather than as a causal determinant.

To capture these structural characteristics, four unweighted centrality measures were used: in-degree, out-degree, betweenness, and closeness. Strength centrality was additionally employed as a weighted measure of trade intensity.

(a) In-degree and out-degree centrality measure the number of supplier and destination links, respectively. In the network visualizations, node size is proportional to in-degree.

$$d_i^{in} = \sum_{j=1}^{N} a_{ji} \tag{2}$$

$$d_i^{out} = \sum_{j=1}^{N} a_{ij} \tag{3}$$

where $a_{ij}$ is 1 if a directed trade flow exists from country $i$ to country $j$, and 0 otherwise, and $N$ denotes the total number of countries (nodes) in the network.

(b) Betweenness centrality measures a country's potential intermediary role within the network (Gönçer-Demiral and İnce-Yenilmez, 2022).

$$I = \frac{2}{(n-1)(n-2)} \sum_{p=1}^{n} \sum_{q=1}^{n} \frac{s_{pq(i)}}{s_{pq}} \tag{4}$$

where $s_{pq}$ is the number of shortest paths between $p$ and $q$, and $s_{pq(i)}$ is the number passing through country $i$.

(c) Closeness centrality measures a country's relative accessibility to other countries that are reachable through directed trade paths. Because the global nickel ore trade network is directed and may contain disconnected components, closeness centrality is calculated using only nodes that are reachable from the focal country. Unreachable nodes are excluded from the distance calculation rather than assigned an arbitrary distance. Thus, the measure captures how efficiently a country can reach other countries within its directed trade-connected portion of the network. Closeness centrality is calculated as:

$$\mathrm{C}_i = \frac{\mathrm{N_R}}{\sum_{j=1}^{n} \mathrm{d_{ij}}} \tag{5}$$

where $\mathrm{N_R}$ is the number of nodes reachable from country $i$, $d_{ij}$ is the length of the shortest directed path from country (i) to country (j), and the summation is performed over all countries (j) that are reachable from country (i).

(c) Strength centrality represents the total value of a country's trade relationships and is used as a supplementary weighted indicator.

To identify groups of countries with closely connected trade relationships within the nickel trade network, community detection was performed using the greedy modularity maximization algorithm implemented in the NetworkX Python library. This algorithm was selected because it is deterministic, thereby facilitating the reproducibility of the identified community structure (Ran et al., 2025; Cruz et al., 2025). The algorithm was applied using the default NetworkX settings, with weight = None, resolution = 1, cutoff = 1, and best = None. Accordingly, the network was treated as unweighted, the standard modularity resolution was used, no minimum number of communities was imposed, and the algorithm identified the community structure that maximized modularity.

### 3.3. Competitiveness measurement

To assess nickel ore export competitiveness, this study employed the Revealed Comparative Advantage (RCA) index developed by Balassa (1965). The RCA index compares the share of nickel ores and concentrates in a country's total exports with the corresponding share of nickel ores and concentrates in total world exports. It was calculated as follows:

$$RCA_{jt} = \frac{\frac{x_{ijt}}{x_{jt}}}{\frac{x_{iwt}}{x_{wt}}} \tag{6}$$

where: $x_{ijt}$ is the export value of nickel ores and concentrates classified under HS 2604 by country $j$ in year $t$; $x_{jt}$ is the total export value of all products by country $j$ in year $t$; $x_{iwt}$ is the total world export value of nickel ores and concentrates classified under HS 2604 in year $t$; and $x_{wt}$ is total world export value of all products in year $t$.

An $RCA_{jt} > 1$ indicates that nickel ore has a larger share in country $j$'s export structure than in the global export structure, thereby indicating revealed comparative advantage. An $RCA_{jt} < 1$ indicates revealed comparative disadvantage, while $RCA_{jt} = 1$ represents a neutral position.

Because the RCA index is asymmetric and has no fixed upper bound, the Revealed Symmetric Comparative Advantage (RSCA) index is used to transform RCA values into a symmetric scale ranging from −1 to +1 (Dalum et al., 1998; Danna-Buitrago and Stellian, 2022):

$$RSCA_{jt} = \frac{RCA_{jt} - 1}{RCA_{jt} + 1} \tag{7}$$

A positive RSCA value indicates revealed comparative advantage in nickel ore exports, whereas a negative value indicates revealed comparative disadvantage. An RSCA value of zero corresponds to RCA = 1 and therefore represents a neutral position. RSCA is used as the primary competitiveness indicator in the subsequent analysis because its symmetric scale facilitates cross-country and intertemporal comparisons.

RCA/RSCA are calculated annually for each country over the 2012-2023 period. These indicators measure product-specific export specialization and should not be interpreted as direct measures of productivity, profitability, processing capacity, or competitiveness across the broader nickel value chain.

### 3.4. Competitiveness dynamics

To examine changes in nickel ore export competitiveness over time, a country-specific time-trend regression is estimated using annual RSCA values for 2012-2023, following Kocourek (2015) and Zhang and Sun (2022):

$$RSCA_{jt} = \beta_{0j} + \beta_{1jt} + \varepsilon_{jt} \tag{8}$$

where $RSCA_{jt}$ is the RSCA value of country $j$ in year $t$, $\beta_{0j}$ is the intercept, $\beta_{1j}$ is the annual rate of change in RSCA, $t$ denotes time, and $\varepsilon_{jt}$ is the error term.

The slope coefficient is calculated as:

$$\beta_{1j} = \frac{n\sum_{t=1}^{n} RSCA_{j,t}t - \left(\sum_{t=1}^{n}\mathrm{t}\right)\left(\sum_{t=1}^{n} RSCA_{j,t}\right)}{n\sum_{t=1}^{n} t^2 - \left(\sum_{t=1}^{n} t\right)^2} \tag{9}$$

where $j$ denotes country, $t$ denotes year, and n = 12, corresponding to the 2012-2023 observation period. A positive $\beta_{1j}$ indicates an improving trend in revealed nickel ore export competitiveness, whereas a negative $\beta_{1j}$ indicates a declining trend. Only coefficients statistically significant at the 5% level are interpreted as evidence of a systematic trend.

Countries are classified into four competitiveness-dynamics categories by comparing their initial RSCA position with the direction of change: maintained advantage, gained advantage, maintained disadvantage, and lost advantage. A country is classified as having gained or lost comparative advantage only when its RSCA crosses the zero threshold during the observation period.

### 3.5. Analytical integration

By combining SNA with RCA/RSCA, this study examines the association between countries' structural positions in the global nickel ore trade network and their revealed export competitiveness. Strength, in-degree, out-degree, betweenness, and closeness centrality identify network position, while RSCA is used as the primary indicator of the level and dynamics of nickel ore export advantage. These dimensions are integrated through Spearman's rank correlation and a reproducible SNA-RSCA classification framework. The analysis focuses on statistical association and structural correspondence rather than causality.

Spearman's rank correlation is employed to examine the association between RSCA and each centrality indicator in the benchmark years 2012, 2018, and 2023. These years represent the initial, intermediate, and final conditions of the study period. Spearman's correlation is appropriate because the indicators are not assumed to follow a normal distribution and the analysis focuses on rank-based relationships. The coefficient ranges from −1 to +1, where positive values indicate that higher centrality tends to be associated with higher RSCA, while negative values indicate an inverse association. Statistical significance is evaluated at the 5%, 1%, and 0.1% levels.

To construct the network-position dimension of the typology, four centrality indicators consistent with the directed and unweighted network specification are used: in-degree, out-degree, betweenness, and closeness centrality. Each indicator is normalized annually using min–max normalization:

$$NC_{ijt} = \frac{C_{ijt} - \min\left(C_{jt}\right)}{\max\left(C_{jt}\right) - \min\left(C_{jt}\right)} \tag{10}$$

where $NC_{ijt}$ is the normalized value of centrality indicator $j$ for country $i$ in year $t$, $C_{ijt}$ is the original centrality value, and $\min(C_{jt})$ and $\max(C_{jt})$ are the annual minimum and maximum values of indicator $j$.

A composite network-position score is then calculated as the unweighted arithmetic mean of the four normalized indicators:

$$NPS_{it} = \frac{NID_{it} + NOD_{it} + NB_{it} + NC_{it}}{4} \tag{11}$$

where $NPS_{it}$ is the composite network-position score, $NID_{it}$ is normalized in-degree, $NOD_{it}$ is normalized out-degree, $NB_{it}$ is normalized betweenness, and $NC_{it}$ is normalized closeness. Equal weighting is applied because the study does not assume that one structural dimension is theoretically more important than the others.

Countries with an *NPS* above the annual median are classified as having a high network position, while countries with an *NPS* equal to or below the annual median are classified as having a low network position. The annual median is used because centrality distributions are highly skewed and may contain dominant outliers. Export competitiveness is classified using RSCA, where RSCA $> 0$ indicates revealed comparative advantage and RSCA $\leq 0$ indicates the absence of revealed comparative advantage.

The combination of network position and RSCA produces four analytical categories, as shown in Table 1.

The term “dependent” in the third category refers to relatively limited structural embeddedness and narrower trade connectivity, rather than a direct measurement of bilateral dependence. The typology therefore identifies convergence and mismatch between structural network position and revealed nickel ore export competitiveness. It does not imply that centrality causes competitiveness.

**Table 1**
SNA-RSCA classification framework for nickel ore trade network position and export competitiveness.

| Network position | Competitiveness criterion | Analytical category | Interpretation |
|---|---|---|---|
| High: ($NPS_{it} >$ annual median) | RSCA $> 0$ | High-network-position/high-RSCA countries | Countries combining relatively strong network embeddedness with revealed comparative advantage in nickel ore exports |
| High: ($NPS_{it} >$ annual median) | RSCA $\leq 0$ | High-network-position/low-RSCA countries | Countries occupying relatively strong structural positions without revealed comparative advantage in nickel ore exports |
| Low: ($NPS_{it} \leq$ annual median) | RSCA $> 0$ | Low-network-position/high-RSCA countries | Countries possessing revealed nickel ore export advantage but relatively limited network embeddedness and market connectivity |
| Low: ($NPS_{it} \leq$ annual median) | RSCA $\leq 0$ | Low-network-position/low-RSCA countries | Countries combining relatively weak network positions with no revealed comparative advantage in nickel ore exports |

Note: NPS is the unweighted mean of annually normalized in-degree, out-degree, betweenness, and closeness centrality. High network position is defined as NPS above the annual median. RSCA $>$ 0 denotes revealed comparative advantage.

## 4. Results and discussion

### 4.1. The global nickel ore trade network

Fig. 1 shows that nickel mine production and reserves are concentrated in a limited number of countries, particularly Indonesia, the Philippines, and New Caledonia. This upstream concentration underscores the importance of resource-rich countries in determining the physical availability of nickel ore, although resource ownership does not automatically translate into a central network position or revealed nickel ore export competitiveness. Meanwhile, China dominates nickel ore imports with an approximately 64% share, followed by Canada, South Korea, Finland, and Japan, which collectively account for most global nickel ore imports.

This contrast reveals an asymmetry between ore-producing countries and major importers, which shape trade direction through the scale and diversity of their sourcing relationships. Similar patterns have been identified in previous studies, with production concentrated among resource-rich exporters and trade flows organized around a smaller group of major importing economies (Ding, 2020; Dong et al., 2021; Ma et al., 2022).

The results also show that resource endowment and network position are not equivalent. An ore-producing country may have strong export specialization but few destination markets, whereas a resource-limited country may occupy a prominent position through extensive import links. Network centrality therefore reflects structural embeddedness rather than comparative advantage itself (Gönçer-Demiral and İnce-Yenilmez, 2022; Dong et al., 2021).

Fig. 2 shows that approximately 60 countries participated in the nickel ore trade network during 2012–2023, while the number of trade

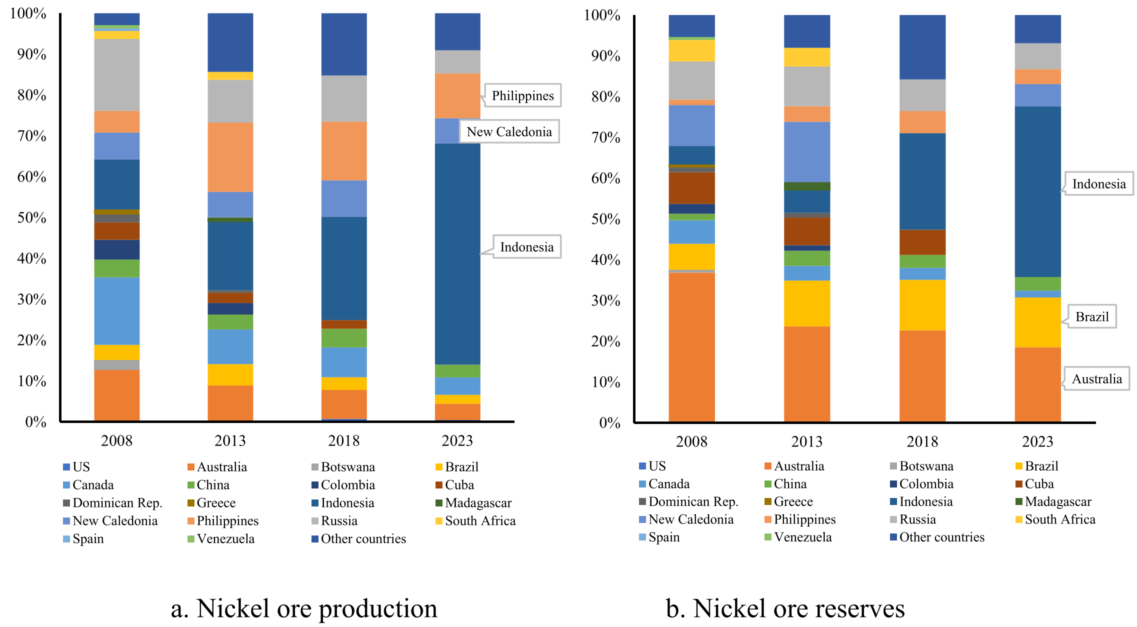


**Fig. 1.** Development of nickel mine production and reserves, 2008-2023.
Source: Authors' calculation based on USGS Mineral Commodity Summaries, 2008-2023.

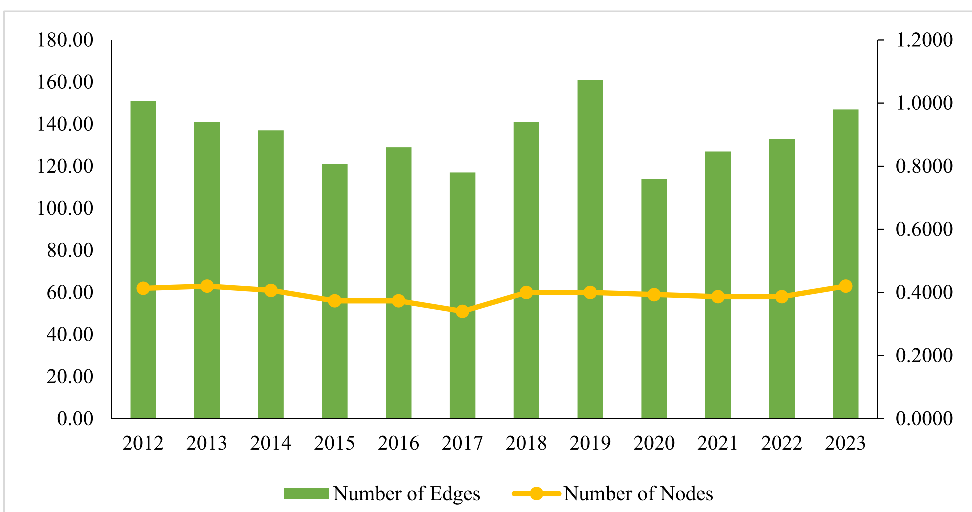


**Fig. 2.** Nodes and edges in the nickel ore trade network.
Source: Authors' calculation based on Trade Map data, 2012-2023.

links changed more substantially. After declining between 2012 and 2015, links recovered and peaked in 2019. This pattern suggests that network evolution occurred mainly through changes in bilateral relationships rather than wider country participation, consistent with evidence of unstable nickel ore trade links (Ma et al., 2022). A larger number of links indicates broader connectivity but does not necessarily imply higher trade volume, lower dependency, or stronger competitiveness, because trade value may remain concentrated in a few relationships (Gönçer-Demiral and İnce-Yenilmez, 2022).

The decline in trade links after 2019 coincided with the COVID-19 pandemic and Indonesia's nickel ore export prohibition, which took effect in 2020. The pandemic disrupted production and logistics, whereas the export restriction reduced Indonesia's participation in international ore trade and redirected demand toward alternative suppliers (Wang et al., 2022; Suryanto, 2022). These shocks affected the network through different channels, with the pandemic creating temporary disruption and the export restriction producing a more structural reallocation of ore flows. Similar evidence shows that policy changes and supply disruptions involving major producers can alter trade allocation and network stability (Dong et al., 2021; Ma et al., 2022; Jia et al., 2024).

Indonesia's declining ore-export links should not be interpreted as weaker performance across its wider nickel sector. Within HS 2604, they reflect a policy-induced shift away from raw-ore exports toward domestic processing rather than a loss of resource capability. Fig. 2 therefore shows that relatively stable country participation can coexist with substantial changes in bilateral links, trading partners, and flow directions following external shocks and industrial-policy interventions.

Fig. 3 presents strength centrality, which captures the intensity of nickel ore trade associated with each country. China records the highest value throughout the study period, reinforcing its role as the principal demand-oriented hub in the HS 2604 network. This finding is consistent

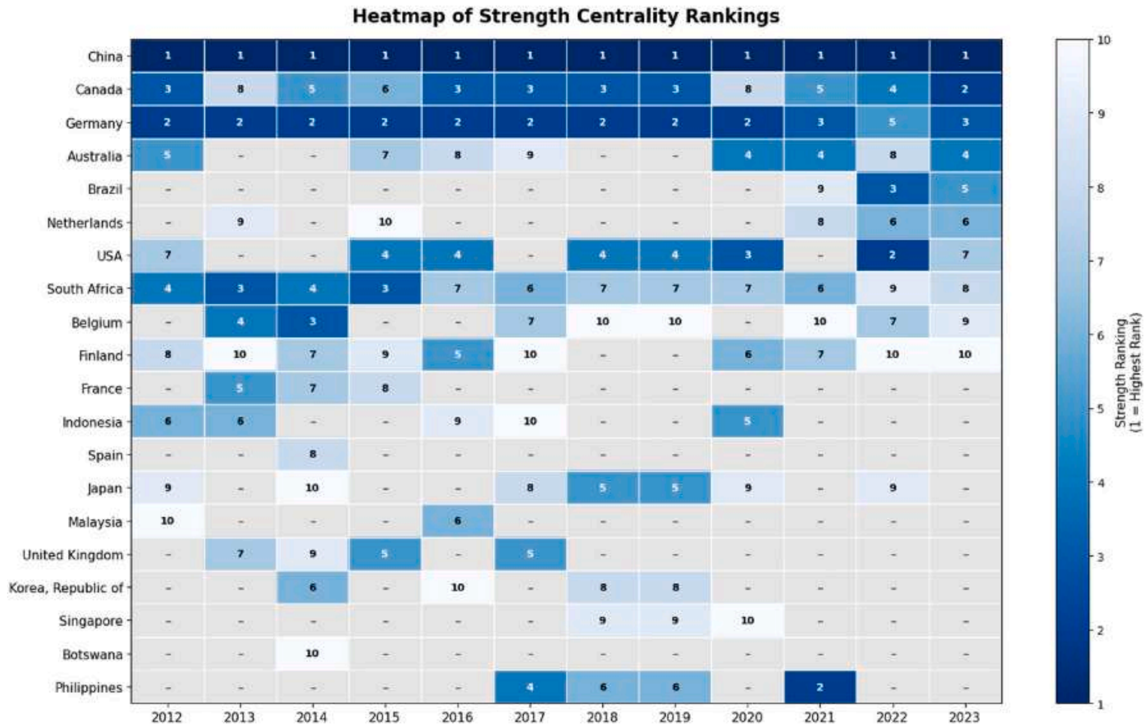


**Fig. 3.** Top 10 countries by strength centrality in the global nickel ore trade network, 2012-2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

with earlier studies that identify China as a major importing and processing centre in international nickel trade (Ding, 2020; Jia et al., 2024).

China's prominence is driven by the large volume of nickel ore directed to its market and by its extensive sourcing relationships with producing countries. In this study, however, high strength denotes the intensity of China's trade connections rather than revealed comparative advantage in nickel ore exports. Its position therefore reflects demand-driven centrality, where network prominence arises from the capacity to attract supply from multiple producing economies rather than from specialization as an ore exporter.

Germany exhibits a different pattern. Its relatively high strength reflects substantial trade relationships with several partners rather than

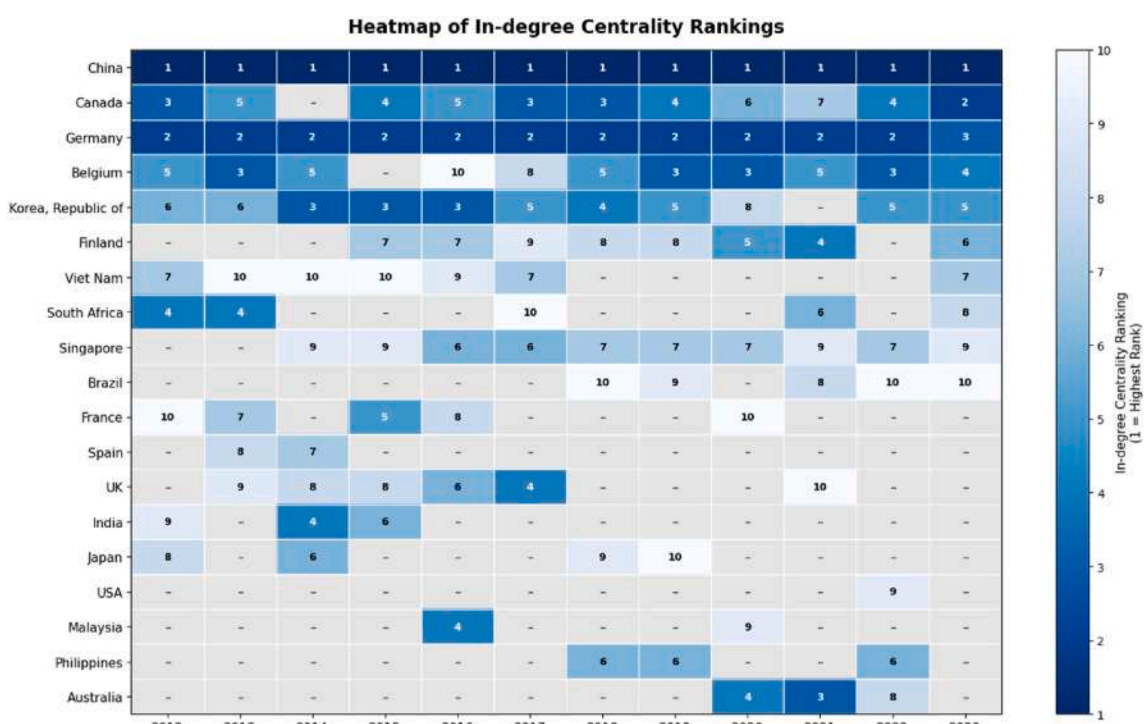


**Fig. 4.** Top 10 countries by in-degree centrality in the global nickel ore trade network, 2012-2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

control over nickel ore resources. This position suggests broad access to external supply channels, although strength alone does not establish whether such connectivity provides bargaining leverage or lowers supply risk. These outcomes depend on the concentration of trade value across suppliers and the availability of credible alternatives.

Finland also occupies a notable position because its import and export relationships connect external ore suppliers with domestic processing activities and international markets. This role remains specific to HS 2604 and should not be interpreted as direct evidence of competitiveness in processed nickel products. More generally, earlier research shows that countries may occupy different structural positions across stages of the nickel product chain, which cautions against extending ore-level centrality to downstream performance (Chen et al., 2024). Canada, South Africa, and the United States display greater variation in their rankings, indicating that positions below the dominant hub are more responsive to changes in bilateral flows, supplier availability, external demand, and relatively small transactions.

Figs. 4 and 5 present in-degree and out-degree centrality. In-degree measures the number of supplier countries connected to an importer, whereas out-degree measures the number of destination markets reached by an exporter. Because both indicators count relationships rather than trade values, they capture the breadth of connectivity rather than the scale or concentration of trade. This distinction is consistent with network-based studies that separate structural position from export competitiveness (Gönçer-Demiral and İnce-Yenilmez, 2022).

China consistently records the highest in-degree, reflecting its broad access to external nickel ore suppliers. A wider supplier base may provide greater flexibility when individual sources become disrupted, but it does not remove import dependence if most trade value remains concentrated in a few relationships. High in-degree should therefore be interpreted as diversified import connectivity rather than low dependency. This interpretation is supported by evidence that economic and political risks can encourage diversification in nickel sourcing relationships (Jia et al., 2024).

The United States records relatively high out-degree in several years, indicating that its reported nickel ore exports reach a comparatively broad set of destinations. Since out-degree counts links rather than values, this pattern may reflect numerous small transactions and should not be treated as evidence of large-scale ore production or export dominance. The contrast with China illustrates how high centrality can arise from opposite sides of the directed network, with China prominent through supplier connectivity and the United States through destination reach.

For resource exporters, broader out-degree may expand market access and reduce exposure to a single buyer, whereas reliance on only one or two destinations may increase sensitivity to demand shifts, policy changes, or bargaining pressure. This distinction is especially relevant for countries with positive RSCA but limited network reach and is consistent with recommendations that importers diversify supply sources while exporters broaden market allocation (Dong et al., 2021)

Across the observation period, China and several European countries, particularly Germany, maintained relatively prominent positions, whereas the Philippines, Canada, the United States, South Korea, Indonesia, and South Africa experienced greater changes in their rankings. This uneven stability suggests a concentrated structure in which a limited group remains strongly connected, while other countries' positions are more sensitive to changes in particular bilateral relationships. Earlier studies also identify core–periphery features in international nickel networks, although evidence covering multiple nickel products is used here only as a broader structural comparison rather than direct evidence for HS 2604 (Chen et al., 2024; Sun et al., 2024).

China's relative stability is supported by sustained import demand and a broad supplier base. Resource exporters, by contrast, may possess substantial production capacity but occupy less stable positions when their market access depends on only a few importing countries. Production leadership therefore does not necessarily confer equivalent structural influence within the trade network.

Fig. 6 presents betweenness centrality. China, Germany, and Canada frequently record relatively high values, indicating greater potential to connect otherwise less directly linked parts of the nickel ore network. China's position is consistent with its extensive supplier links and central importing role, while Germany and Canada connect different groups of

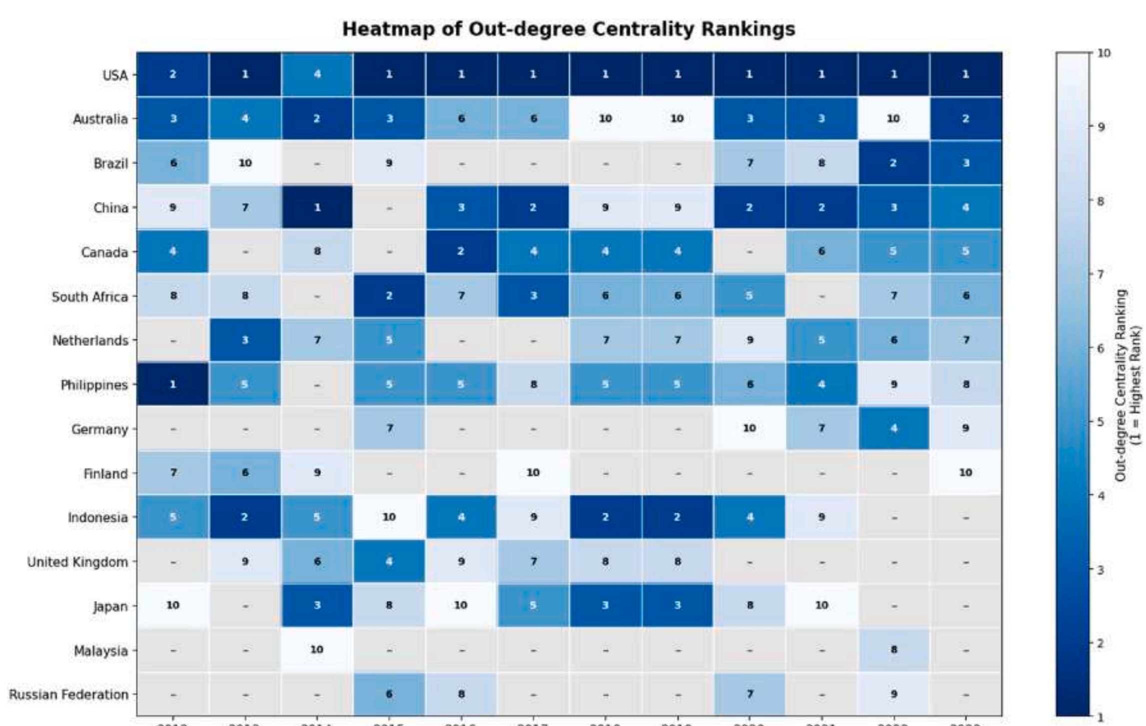


**Fig. 5.** Top 10 countries by out-degree centrality in the global nickel ore trade network, 2012-2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

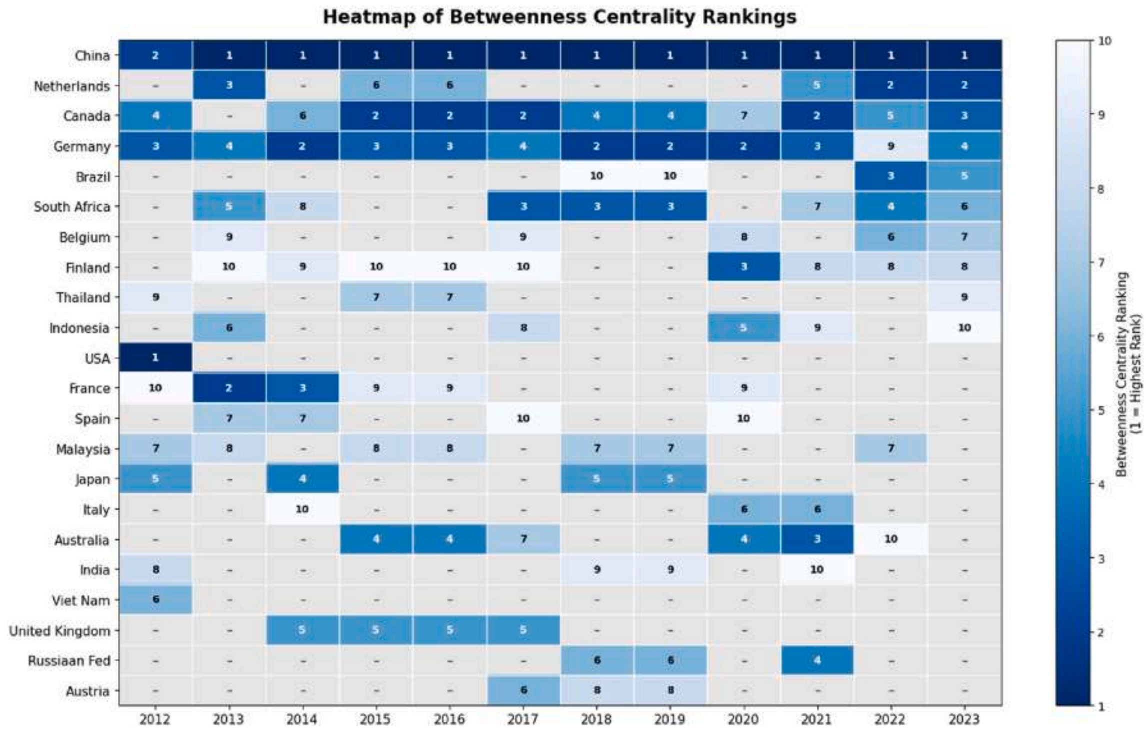


**Fig. 6.** Top 10 countries by betweenness centrality in the global nickel ore trade network, 2012-2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

trading partners less persistently.

Betweenness captures structural brokerage potential rather than control over prices, contracts, or physical ore flows. A country may therefore occupy an intermediary position without recording the largest trade value. This indicator should be interpreted alongside strength, in-degree, and out-degree rather than as a stand-alone measure of trade power.

Fig. 7 presents closeness centrality, which measures each country's relative accessibility to other reachable countries in the directed nickel ore trade network. China consistently records a high value, reflecting its short direct or indirect paths to much of the network and its extensive links with major ore suppliers.

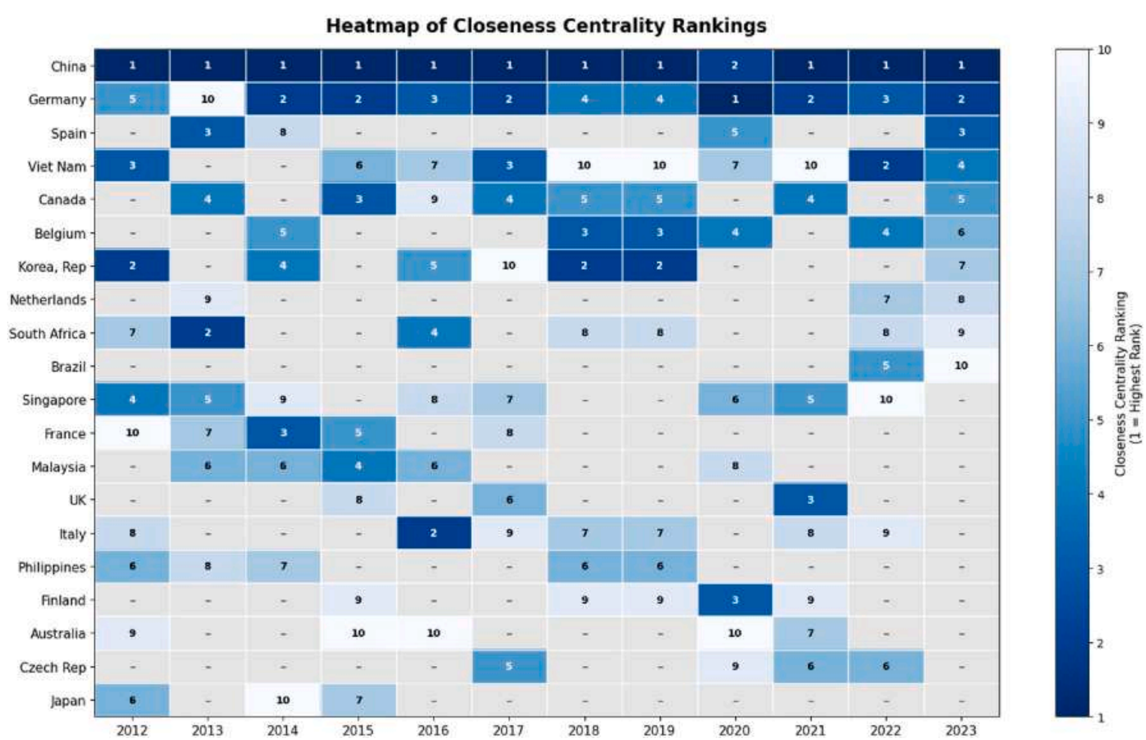


**Fig. 7.** Top 10 countries by closeness centrality in the global nickel ore trade network, 2012-2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

Higher closeness indicates structural accessibility but should not be interpreted as direct evidence of resilience, information advantage, flexibility, or export competitiveness (Gönçer-Demiral and İnce-Yenilmez, 2022). China's high closeness, together with its strength, in-degree, and betweenness, shows that its prominence extends across several structural dimensions, whereas other countries may rank highly on only one indicator.

Figs. 3–7 reveal that structural prominence in the global nickel ore trade network is multidimensional. China combines high trade intensity, broad supplier connectivity, brokerage potential, and network accessibility, whereas other countries may be prominent only through destination reach, supplier breadth, or intermediary position. This variation shows that no single centrality measure can represent trade power or export competitiveness. Import-oriented hubs may be structurally central without possessing revealed comparative advantage in nickel ore exports, while resource-specialized exporters may retain positive RSCA despite limited connectivity. The correlation and SNA-RSCA analyses that follow examine this divergence more directly.

### 4.2. Core countries and trade patterns

Degree-centrality results place China, Germany, and the United States among the most highly connected actors, although their positions are shaped by different trade relationships. China and Germany are characterized mainly by broad supplier-side connectivity, whereas the United States reaches a comparatively wide set of reported export destinations in several years. Since degree centrality counts links rather than trade values, these positions capture the breadth of participation rather than trade dominance. Their relatively high betweenness and closeness values further suggest brokerage potential and structural accessibility, but not direct control over transactions or demonstrated supply-chain resilience.

Figs. 8 and 9 trace how these positions and their surrounding trade relationships evolved between 2012 and 2023. By 2023, the network comprised 63 participating countries and retained a core–periphery structure centred on a limited group of highly connected actors. China remained the principal core country, while Germany and the United States occupied important but structurally different roles. The persistence of this concentrated core, despite changing bilateral links, accords with earlier evidence that nickel ore trade is organized around a relatively small number of major suppliers and demand centres (Ding, 2020; Ma et al., 2022).

Changes in ore supply and trade policy also reshaped these relationships. In 2012, Indonesia and the Philippines were among China's main nickel ore suppliers. Indonesia's subsequent export restrictions reduced its direct participation as an HS 2604 exporter and raised the importance of alternative sourcing relationships, particularly with the Philippines. This shift demonstrates how intervention in a major producing country can redirect trade allocation and alter the relative position of other suppliers (Dong et al., 2021; Jia et al., 2024).

The resulting relationship was interdependent but asymmetric. China relied on foreign ore to support domestic demand, while several exporters depended heavily on access to the Chinese market. Its broad supplier base provided greater scope to adjust sourcing when individual relationships were disrupted, whereas exporters serving only a few destinations remained more exposed to changes in buyer demand or import policy. The network thus combined concentrated demand with unequal levels of diversification on the supply and destination sides.

The red-node group in Fig. 8 includes Canada, South Africa, Australia, and Brazil. Their importance derives from their contribution

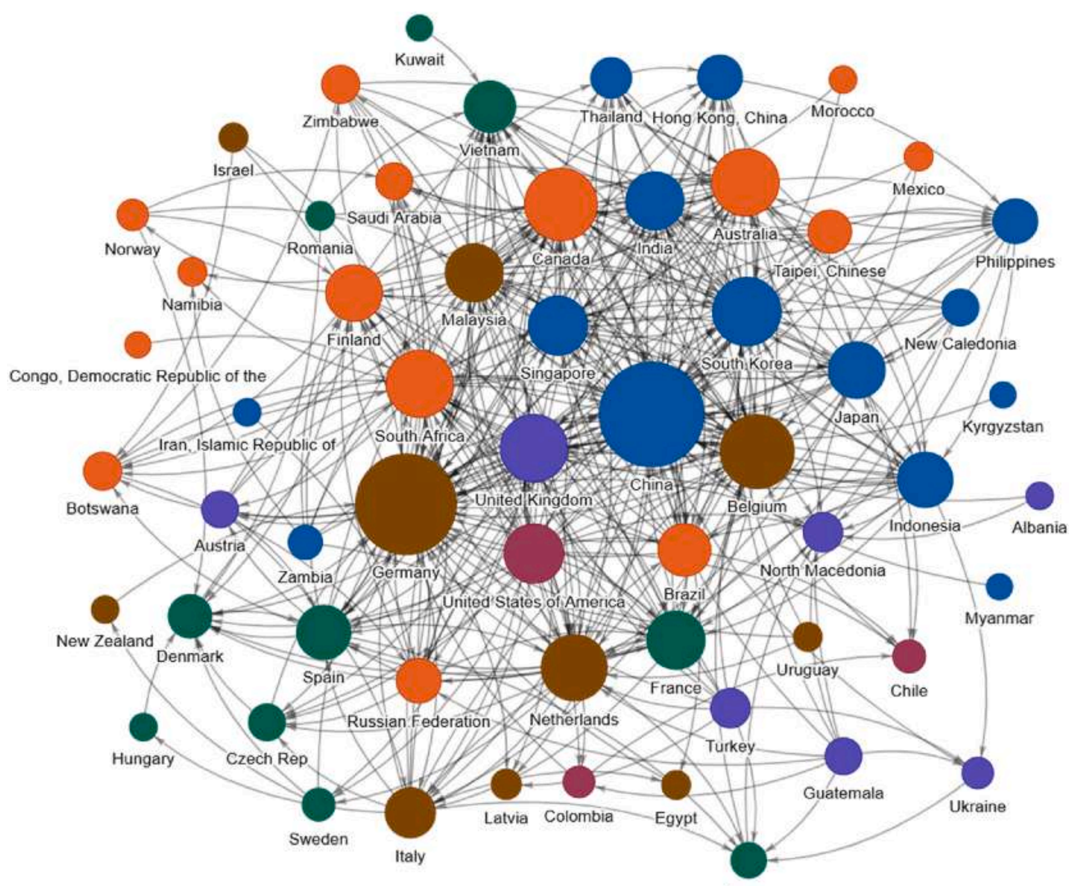


**Fig. 8.** Global nickel ore trade network structure and trade communities in 2012.
Source: Authors' calculation based on Trade Map data, 2012-2023.

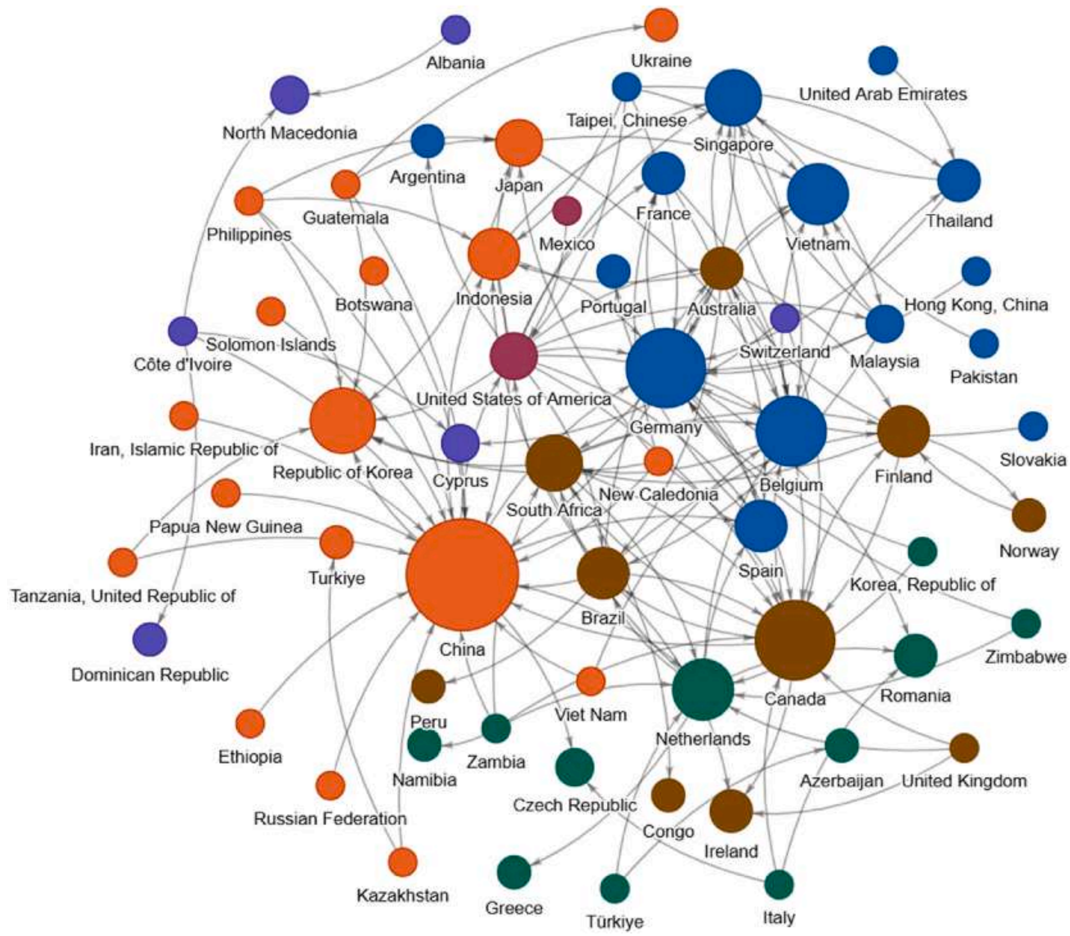


**Fig. 9.** Global nickel ore trade network structure and trade communities in 2023.
Source: Authors' calculation based on Trade Map data, 2012-2023.

to ore supply and circulation rather than from a shared downstream function. Differences within the group stem from variation in destination reach, bilateral trade intensity, and access to major importers. Resource availability can support export participation, but it does not remove the vulnerability associated with dependence on a narrow set of markets.

In 2023, the Philippines, New Caledonia, South Africa, Canada, Australia, and other resource-producing countries remained visible suppliers, while China continued to dominate the import side. Indonesia no longer occupied its earlier position as a leading raw-ore exporter because its HS 2604 role had shifted under a domestic-processing strategy. Compared with 2012, the main hub remained stable, but supplier relationships changed substantially as export policy, Asian demand, geopolitical uncertainty, and ore availability altered trade flows (Ma et al., 2022; Jia et al., 2024).

The 2023 network combined broader sourcing options with continued concentration around key actors. Additional suppliers and links expanded the range of relationships, yet dependence on a small group of producing countries and on China as the principal destination preserved systemic exposure. This should not be interpreted as improved resilience, which requires direct assessment of the network's capacity to absorb and recover from shocks (Yu et al., 2023). Exporters with wider market reach may reduce reliance on a single buyer, while those serving only a few destinations remain more sensitive to policy and demand changes.

Figs. 10–12 present the community structures for 2012, 2018, and 2023. Each community contains countries with denser internal trade relationships than connections to the rest of the network. Membership may be shaped by repeated bilateral trade, geographical proximity, shared supply–demand relationships, or links to the same major hub. It should therefore be understood as a structural trade association rather than a formal political or economic alliance.

In 2012, six communities were identified. One connected Russia, Australia, Canada, Mexico, and South Africa, while another included Indonesia, the Philippines, China, India, and several other Asian countries. The latter was organized largely around China's import demand and nearby ore suppliers. Indonesia and the Philippines held prominent positions because resource availability and geographical proximity supported recurrent trade with the Chinese market. This arrangement reveals strong complementarity between resource suppliers and a major importer, while also concentrating regional trade around a dominant destination.

In 2018, the network consolidated into four communities. One included the United States, Brazil, Mexico, Thailand, Japan, and other connected countries, while another grouped China, Russia, South Africa, Canada, Finland, and several additional partners. The smaller number of communities suggests that previously distinct groups became more interconnected or increasingly organized around fewer hubs. This transition coincided with greater trade uncertainty and adjustments in global sourcing, although the community results do not establish a direct causal effect from the China–US trade dispute. The persistence of China-centred relationships instead points to ore demand as a stronger organizing force than bilateral political tension alone.

By 2023, six communities had re-emerged, but their composition differed from that of 2012. A major Asian-centred group included China, the Philippines, New Caledonia, Japan, Indonesia, and other regional

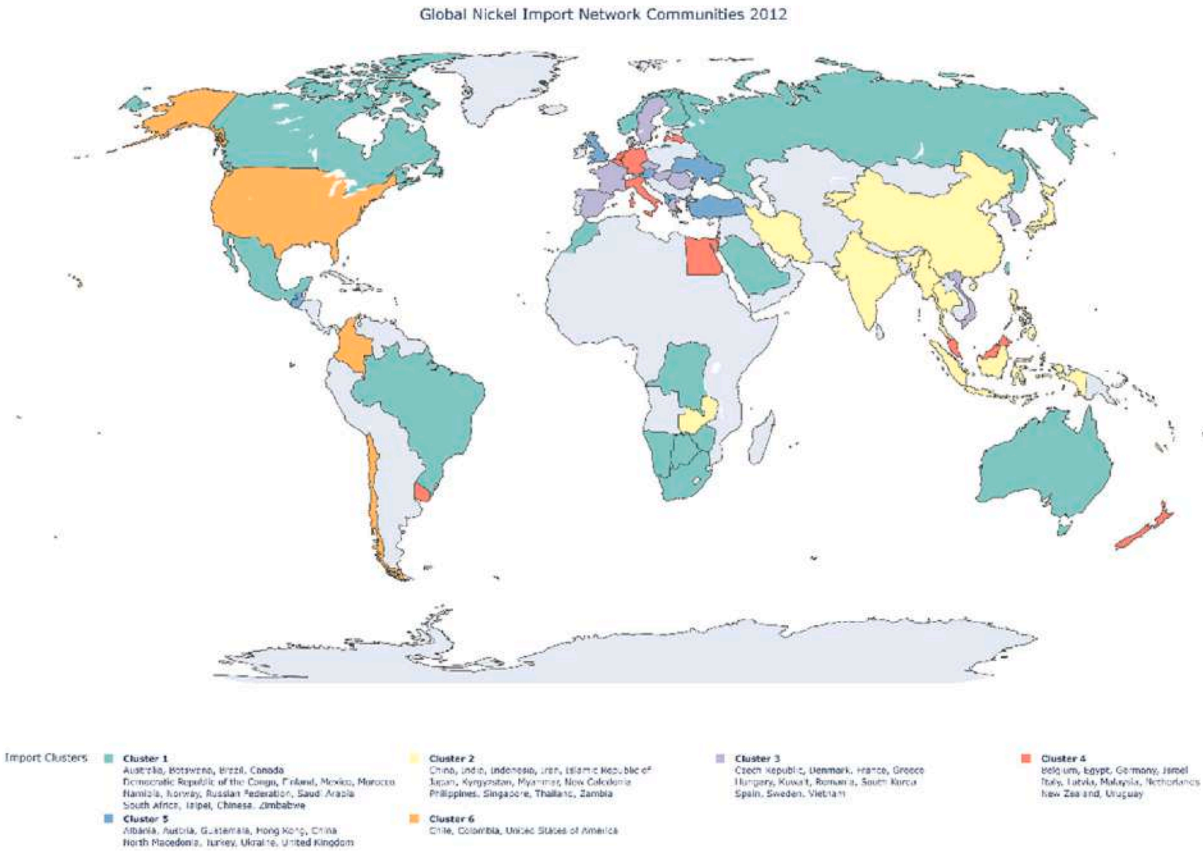


**Fig. 10.** Evolution of trade communities in the global nickel ore trade network, 2012.
Notes: Different colours indicate distinct import trade communities. Countries shown in the same colour belong to the same community in the corresponding year. White areas indicate countries that are not classified in the nickel ore import network.
Source: Authors' calculation based on Trade Map data, 2012-2023.

participants. Indonesia's membership does not imply a return to its former role as a dominant ore exporter; it captures the HS 2604 relationships recorded after the implementation of its downstream-oriented policy. Other communities linked countries across Europe, Africa, and the Americas, showing that geographical proximity remained relevant but did not fully determine grouping. Shared trading partners and indirect connections through bridging countries also shaped community membership.

Comparison across the benchmark years confirms that these communities were fluid rather than permanent. Countries moved between groups as supply conditions, trade policies, and bilateral relationships changed, while China remained the main anchor of the largest ore-trade community. This continuity demonstrates that concentrated import demand continued to organize the network even as supplier composition evolved.

The core–periphery and community analyses distinguish several sources of structural relevance. China's position is sustained by concentrated demand and a broad supplier base, whereas resource exporters derive importance from ore availability and access to destination markets. Germany, the United States, and Canada occupy relevant positions through connectivity or brokerage, but these roles do not necessarily coincide with revealed comparative advantage in nickel ore exports. The following section examines this divergence more directly through Spearman correlation and the SNA–RSCA classification.

### 4.3. Network position and nickel ore export competitiveness

The relationship between network position and the competitiveness of nickel ore exports is examined using Spearman's rank correlation. Table 2 reports the coefficients between RSCA and five centrality measures for 2012, 2018, and 2023, allowing an empirical assessment of whether structurally prominent countries also tend to possess stronger revealed advantage in HS 2604 exports.

RSCA is positively and significantly associated with strength centrality in all three benchmark years, with coefficients of 0.352 in 2012, 0.563 in 2018, and 0.359 in 2023. Countries with a stronger correlation revealed comparative advantage in nickel ore exports therefore tend to participate in more intensive ore trade flows. However, this relationship should be interpreted with caution because both measures are partly derived from nickel ore trade values, which may contribute to the observed association. Strength captures the overall value intensity of a country's bilateral trade relationships, whereas RSCA measures the relative importance of HS 2604 in the country's export structure, benchmarked against the corresponding global market. These dimensions may reinforce one another, but they are conceptually and mathematically/statistically distinct and should not be interpreted as evidence of causal effects (Gönçer-Demiral and İnce-Yenilmez, 2022).

Out-degree is also positively related to RSCA, with coefficients of 0.268 in 2012, 0.441 in 2018, and 0.417 in 2023. The stronger relationship after 2012 suggests that access to a broader range of destination markets is particularly relevant to the revealed ore-export advantage. Multiple destinations can provide exporters with greater scope to redirect sales when demand, regulation, or sourcing conditions change, which accords with the importance of alternative trading partners in the international nickel ore network (Dong et al., 2021). Out-degree, nevertheless, counts destinations rather than export-value shares so that several links may coexist with a heavy reliance on one principal buyer.

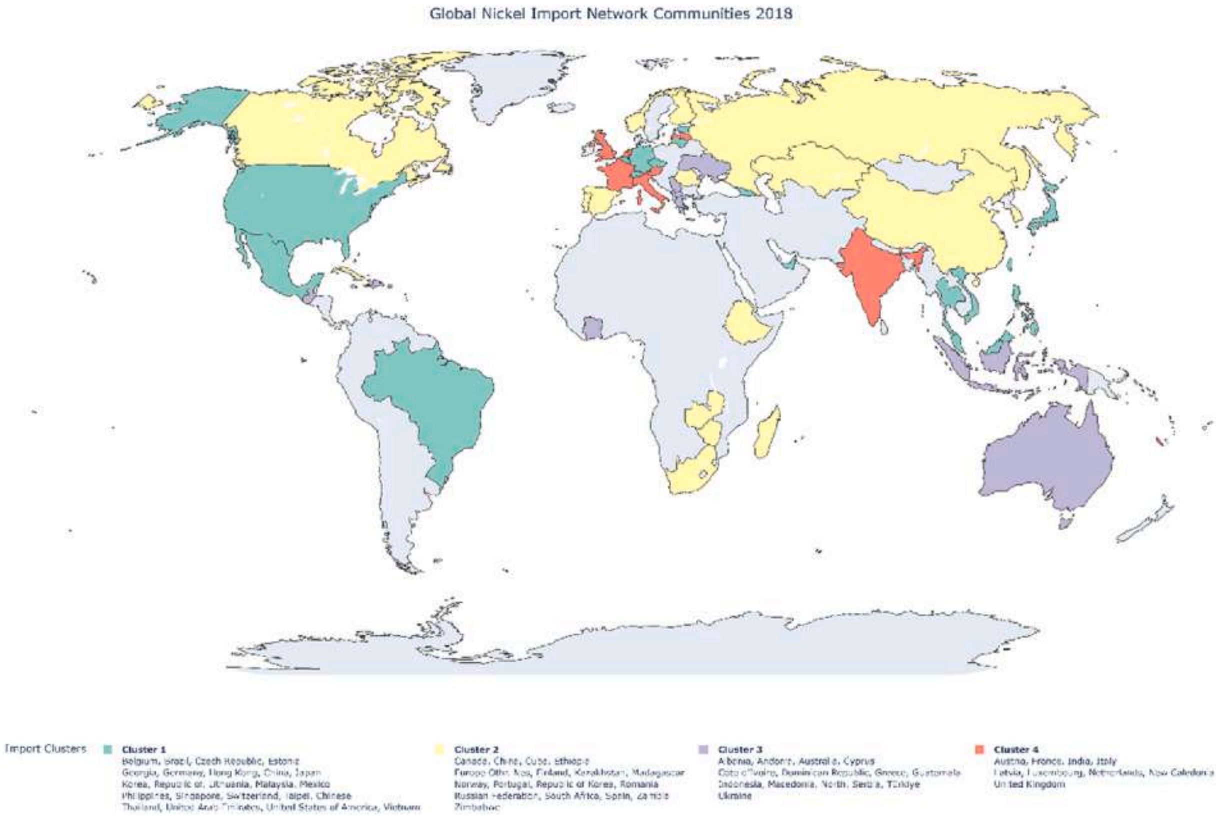


**Fig. 11.** Evolution of trade communities in the global nickel ore trade network, 2018.
Notes: Different colours indicate distinct import trade communities. Countries shown in the same colour belong to the same community in the corresponding year. White areas indicate countries that are not classified in the nickel ore import network.
Source: Authors' calculation based on Trade Map data, 2012-2023.

By contrast, in-degree, betweenness, and closeness show weak, statistically insignificant relationships with RSCA across the benchmark years. Broad access to suppliers, brokerage potential, and proximity to other network actors do not, by themselves, produce a revealed advantage in nickel ore exports. These attributes may instead characterize importing hubs or intermediary economies whose relevance rests on demand, sourcing capacity, or structural accessibility. Overall, the results indicate that trade value and destination reach are more closely associated with export competitiveness than import side connectivity position, while the relationship between strength and RSCA should be interpreted cautiously because of their partial overlap in underlying trade values.

Table 3 examines this distinction at the country level by combining RSCA with the composite network-position score. Countries are assigned to four categories based on whether their annual network score is above, at, or below the median and whether RSCA is positive or non-positive. The resulting groups are high-network-position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries.

The classification separates structural prominence from revealed ore-export advantage. China, Germany, Japan, and several other highly connected economies appear as high-network-position/low-RSCA countries in one or more benchmark years because their composite scores exceed the annual median while their RSCA values remain non-positive. Their importance within the network is associated primarily with sourcing relationships, accessibility, or intermediary roles rather than with a comparatively large share of nickel ore in their export structures. This interpretation is confined to HS 2604 and does not extend to refined nickel or other downstream products.

The opposite configuration is found among New Caledonia, Zimbabwe, Guatemala, Côte d'Ivoire, Namibia, Zambia, and other resource-oriented exporters that record positive RSCA but remain below the annual median network score in at least one benchmark year. Their revealed export advantage is not matched by equally broad connectivity, which may leave them more exposed to changes in a limited set of destination markets. Such countries possess a strong ore-export profile but fewer options for reallocating trade when a major buyer changes its demand or policy. This distinction supports the argument that exporters benefit not only from resource-based advantage but also from wider market allocation (Dong et al., 2021).

In 2012, Australia, Brazil, Finland, Indonesia, the Philippines, Spain, and North Macedonia combined positive RSCA with above-median network positions. By 2018, the group comprised Australia, Belgium, Canada, Finland, Indonesia, and the Philippines. This changing composition suggests that strategic positioning can emerge from different combinations of export advantage and network reach.

The 2023 classification presents a different configuration. Brazil, Finland, and the United States fall within the high-network-position/high-RSCA countries, while the Philippines and New Caledonia retain positive RSCA but move into the low-network-position/high-RSCA countries because their composite network scores remain below the annual median. Indonesia shifts to the high-network-position/low-RSCA countries category as its RSCA becomes non-positive while its structural position remains relatively strong. This movement is better understood as a reorientation of Indonesia's upstream trade role under export restrictions and domestic-processing policy than as weaker performance across its wider nickel industry. Suryanto (2022) similarly reports a weakening of Indonesia's revealed advantage in raw nickel exports during periods affected by export restrictions.

The United States requires cautious interpretation because its 2023 RSCA is only slightly above zero, and its composite position is strongly influenced by broad out-degree connectivity. Its placement among high-

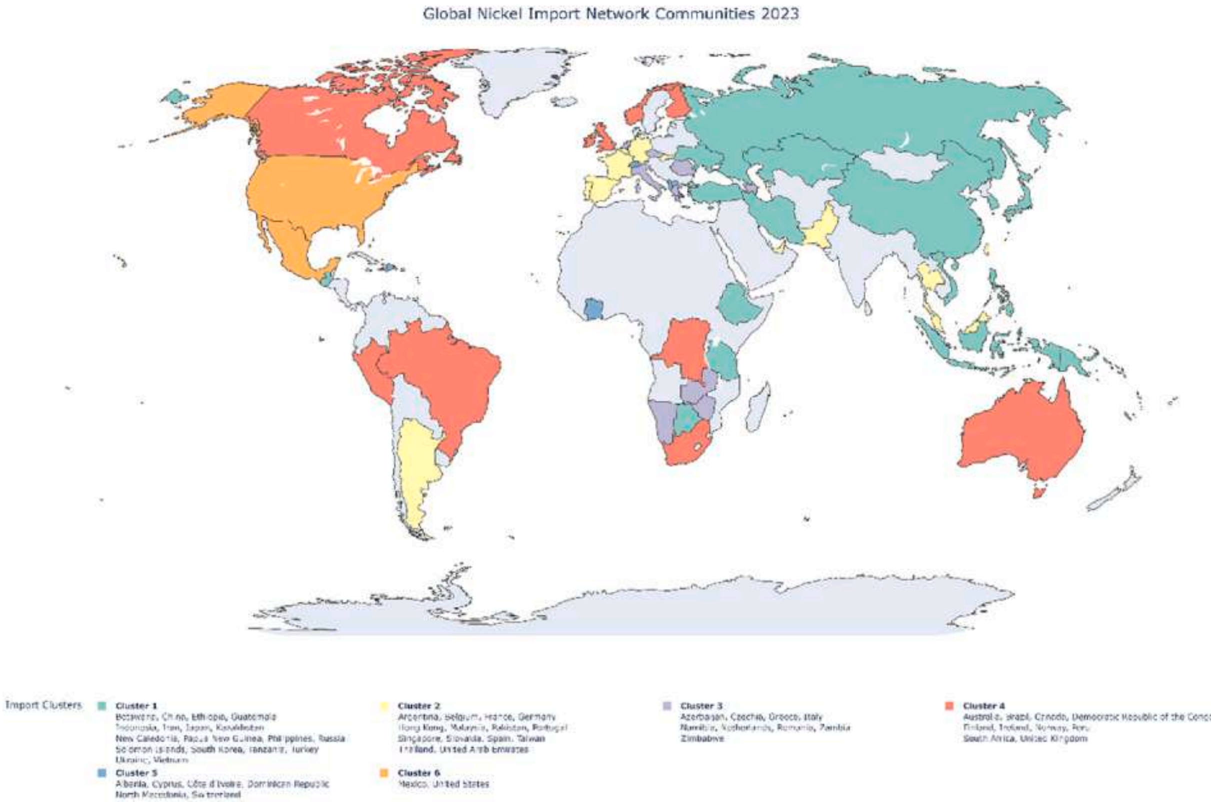


**Fig. 12.** Evolution of trade communities in the global nickel ore trade network, 2023.
Notes: Different colours indicate distinct import trade communities. Countries shown in the same colour belong to the same community in the corresponding year. White areas indicate countries that are not classified in the nickel ore import network.
Source: Authors' calculation based on Trade Map data, 2012-2023.

**Table 2**
Spearman correlations between RSCA and network position measures.

| Year | Strength | In-degree | Out-degree | Betweenness | Closeness |
|---|---|---|---|---|---|
| 2012 | 0.352** | 0.081 | 0.268* | 0.197 | 0.083 |
| 2018 | 0.563*** | 0.205 | 0.441** | 0.231 | 0.223 |
| 2023 | 0.359* | −0.173 | 0.417** | −0.017 | −0.201 |

Notes: Spearman's rank correlation coefficients are reported. RSCA denotes revealed symmetric comparative advantage in nickel ores and concentrates under HS 2604. Strength is retained as a supplementary weighted indicator of trade intensity and is not included in the composite network-position score. *, **, and *** indicate statistical significance at the 5%, 1%, and 0.1% levels, respectively.

network-position/high-RSCA countries follows the predefined classification thresholds and should not be read as evidence of dominant primary ore production. Small transactions, redistribution, or re-export activity may contribute to this outcome, although the available indicators cannot distinguish among these mechanisms.

Changes across the benchmark years reveal that network position and export competitiveness evolve through different channels. Positive RSCA is associated with the relative importance of nickel ore in a country's exports, while network position depends on the breadth, intensity, and structural arrangement of its trade relationships. Countries combining both dimensions occupy the strongest strategic category. Mismatches, however, expose two distinct conditions: structurally prominent economies without an ore-export advantage and resource-competitive exporters without broad network reach. Spearman correlation captures the general relationship between these dimensions, while the SNA-RSCA typology identifies the country-level cases behind their convergence and divergence without implying causality.

## 5. Conclusions

This study examined how the structure of the global nickel ore trade network evolved between 2012 and 2023 and whether countries' network positions corresponded with their revealed export competitiveness. By combining social network analysis with RCA/RSCA, it demonstrates that prominence in the HS 2604 trade network and specialization in nickel ore exports represent distinct dimensions of international trade performance. A country may occupy an important structural position because of its extensive import or intermediary connections without possessing a revealed export advantage, while a resource-based exporter may remain weakly embedded despite strong specialization in nickel ore trade.

The results indicate that the network continued to be organized around a relatively small group of highly connected economies, even as bilateral links and community structures changed over time. The relationship between network position and competitiveness was selective rather than uniform. RSCA was consistently associated with trade strength and out-degree, indicating that competitive exporters tended to combine substantial trade intensity with access to a wider set of destination markets. In-degree, betweenness, and closeness did not show the same consistent relationship, confirming that import connectivity, brokerage potential, or network proximity should not be treated as direct evidence of export competitiveness.

The SNA–RSCA typology clarifies these differences by separating high-network- position/high-RSCA countries, high-network-position/low-RSCA countries, low-network-position/high-RSCA countries, and low-network-position/low-RSCA countries. The 2023 classification places Brazil, Finland, and the United States among countries combining positive RSCA with above-median network positions, while the Philippines and New Caledonia retained revealed export advantage but

**Table 3**
Classification of countries by network position and nickel ore export competitiveness.

| Year | High-network-position/high-RSCA countries ($NPS_{it} > \widetilde{NPS}_t$; RSCA > 0) | High-network-position/low-RSCA countries ($NPS_{it} > \widetilde{NPS}_t$; RSCA ≤ 0) | Low-network-position/high-RSCA countries ($NPS_{it} \leq \widetilde{NPS}_t$; RSCA > 0) | Low-network-position/low-RSCA countries ($NPS_{it} \leq \widetilde{NPS}_t$; RSCA ≤ 0) |
|---|---|---|---|---|
| 2012 | Australia; Brazil; Finland; Indonesia; Philippines*; Spain; North Macedonia* | Belgium; Canada; China; Denmark*; France; Germany; Hong Kong, China*; India; Italy; Japan; Malaysia; Netherlands; Russian Federation*; Singapore; South Africa; South Korea; Thailand*; United Kingdom; United States of America*; Vietnam* | Austria*; Chile; Guatemala; New Caledonia; Zimbabwe* | Albania; Botswana*; Chinese Taipei; Colombia; Czech Republic*; Democratic Republic of the Congo; Egypt; Greece*; Hungary; Iran; Israel; Latvia*; Mexico; Morocco; Myanmar; Namibia; Norway; Romania; Saudi Arabia*; Sweden; Türkiye; Ukraine; Zambia |
| 2018 | Australia; Belgium*; Canada; Finland; Indonesia; Philippines* | Brazil; China; France; Germany; India; Italy; Japan; Malaysia; Netherlands; North Macedonia*; Republic of Korea; Russian Federation*; Singapore | Côte d'Ivoire; Guatemala; New Caledonia | Albania; Austria*; Cuba; Czech Republic; Estonia; Ethiopia; Greece*; Hong Kong, China; Kazakhstan; Latvia*; Lithuania; Madagascar; Mexico; Norway; Portugal*; Romania |
| 2023 | Brazil; Finland; United States of America* | Australia; Belgium; Canada*; China; Democratic Republic of the Congo*; Czech Republic; France; Germany; Greece*; Indonesia; Japan*; Malaysia; Netherlands; Portugal*; Romania; Singapore; South Africa; Spain; Thailand | Côte d'Ivoire; Guatemala; Namibia; New Caledonia*; Philippines; Zambia*; Zimbabwe | Albania; Botswana; Cyprus; Ethiopia; Hong Kong, China; Iran; Italy; Kazakhstan; Mexico; North Macedonia; Pakistan; Switzerland; Chinese Taipei*; United Arab Emirates; United Kingdom |

Notes: $NPS_{it}$ denotes the composite network-position score of country $i$ in year $t$, and $\widetilde{NPS}_t$ denotes the annual median. $RSCA_{it} > 0$ indicates revealed comparative advantage in nickel ores and concentrates under HS 2604, whereas $RSCA_{it} \leq 0$ indicates no revealed comparative advantage. An asterisk indicates a borderline case, defined as $|RSCA_{it}| \leq 0.05$ or an $NPS_{it}$ value within ±0.05 of the annual median. The Republic of Korea and the Russian Federation are excluded from the 2023 classification because their RSCA values are unavailable.
Source: Authors' calculation based on Trade Map data, 2012-2023.

occupied weaker structural positions. Indonesia moved into the high-network-position/low-RSCA countries category as its role in HS 2604 trade changed under an industrial strategy oriented toward domestic processing. These shifts show that changes in raw-ore competitiveness may reflect a reconfiguration of trade orientation rather than a simple gain or loss of national capability.

The study's principal contribution is to show that nickel ore competitiveness cannot be inferred from resource endowment, export value, or centrality alone. It depends on the interaction of export specialization, destination reach, trade intensity, and network position. The framework distinguishes countries combining market reach and export advantage from those whose importance rests mainly on demand, connectivity, or narrow resource-based specialization.

## 6. Policy implications

The findings suggest that nickel ore policy should be considered within the broader value chain rather than based on HS 2604 trade performance alone. Ore demand is shaped by processing capacity, industrial investment, technological requirements, and downstream demand from stainless-steel and battery-related industries. A country's network position therefore reflects not only resource endowment and market access but also the location and development of processing activities.

The SNA-RSCA matrix can serve as a diagnostic instrument for differentiating policy priorities. high-network-position/high-RSCA countries should protect access to multiple processing centres and destination markets through reliable infrastructure, transparent ore-quality information, and diversified commercial relationships. Low-network-position/high-RSCA countries require more active market development, trade facilitation, and engagement with alternative buyers, as their export advantage is only weakly supported by network connectivity. High-network-position/low-RSCA countries should focus on supply security through diversified sourcing, long-term contracts, strategic inventories where appropriate, recycling, and investment partnerships. Low-network-position/low-RSCA countries should first establish geological, commercial, and logistical viability before committing public resources to export expansion or domestic processing.

These options are increasingly conditioned by resource nationalism and the securitization of critical-mineral supply chains. Export restrictions, domestic-processing requirements, friend-shoring, strategic mineral partnerships, rules of origin, and long-term offtake arrangements can redirect ore flows independently of conventional comparative advantage. Indonesia provides a prominent example: its downstreaming programme and more inward-oriented industrial strategy altered its role in the nickel ore network, while also generating tension with multilateral trade disciplines. The decline of its HS 2604 competitiveness should therefore be read as a change in trade orientation, not as a sufficient measure of the performance of its wider nickel industry.

Environmental commitments add another layer to policy design. Countries differ in their nationally determined contributions, energy mixes, regulatory capacity, technological resources, and development priorities. Policies that promote domestic processing may create value and improve supply-chain positioning, but they may also raise emissions and environmental pressures when processing depends on carbon-intensive energy. Exporters seeking access to lower-carbon supply chains will increasingly need traceability, credible environmental standards, and compatibility with destination-market requirements and preferred trading blocs.

The classification should consequently be reviewed over time rather than treated as a permanent ranking. Borderline countries may move between categories after relatively small changes in RSCA or network position, while shifts in downstream technology, alliances, environmental regulation, or industrial policy may rapidly alter the value of existing trade relationships. The matrix identifies the principal form of trade capacity or vulnerability, but the appropriate policy response must remain consistent with each country's industrial capabilities, international commitments, and environmental constraints.

This study focuses on country-level trade in nickel ores and concentrates under HS 2604; accordingly, its findings reflect upstream trade positioning rather than the performance of the wider nickel industry. The SNA–RSCA classification should also be interpreted as a relative annual assessment, since category membership may be affected by data coverage and values close to the classification thresholds. Future research could extend this framework to processed nickel products, recycling flows, firm-level networks, and longitudinal models capable of examining how industrial policy, strategic partnerships, and environmental requirements reshape the broader nickel value chain.

## CRediT authorship contribution statement

**Reninta Dewi Nugraheni:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Iwan Hermawan:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Carunia Mulya Firdausy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Shiddiq Sugiono:** Writing – original draft, Software, Methodology, Formal analysis, Conceptualization.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We gratefully acknowledge the anonymous editor and the two anonymous reviewers for their insightful comments and constructive suggestions, which helped us significantly improve the quality of this manuscript. Any remaining errors are ours.

## Data availability

Data will be made available on request.

## References

Balassa, B., 1965. Trade liberalisation and revealed comparative advantage. Manch. Sch. 33 (2), 99–123. https://doi.org/10.1111/j.1467-9957.1965.tb00050.x.

Basuhi, R., Bhuwalka, K., Moore, E.A., Diersen, I., Malik, R.H., Young, E., Billy, R.G., Stoner, R., Ceder, G., Müller, D.B., Roth, R., Olivetti, E.A., 2024. Clean energy demand must secure a sustainable nickel supply. Joule 8 (11), 2960–2973. https://doi.org/10.1016/j.joule.2024.10.008.

Chen, W., Jiang, Y., Liu, Z., 2024. Unveiling structural differentiation in the global nickel trade network: a product chain perspective. J. Geogr. Sci. 34, 763–778. https://doi.org/10.1007/s11442-024-2226-y.

Cingolani, I., Panzarasa, P., Tajoli, L., 2017. Countries' positions in the international global value networks: centrality and economic performance. Appl.Network Sci. 2, 21. https://doi.org/10.1007/s41109-017-0041-4.

Coveri, A., Paglialunga, E., Zanfei, A., 2024. Global value chains and within-country inequality: the role of functional positioning. Struct. Change Econ. Dynam. 70, 382–397. https://doi.org/10.1016/j.strueco.2024.05.001.

Coveri, A., Zanfei, A., 2023. The virtues and limits of specialization in global value chains: analysis and policy implications. J.Industrial Bus. Econ. 50 (1), 73–90. https://doi.org/10.1007/s40812-022-00247-9.

Cruz, M., Carvalho, R., Costa, A., Pinto, L., Dias, L., Cerqueira, P., Machado, R., Batista, T., Castro, P., Ribeiro, J., 2025. A contribution of shortest paths algorithms to the NetworkX Python Library. Appl. Sci. 15 (15), 8273. https://doi.org/10.3390/app15158273.

Dalum, B., Laursen, K., Villumsen, G., 1998. Structural change in OECD export specialisation patterns: De-specialisation and 'stickiness'. Int. Rev. Appl. Econ. 12 (3), 423–443. https://doi.org/10.1080/02692179800000017.

Danna-Buitrago, J.P., Stellian, R., 2022. A new class of revealed comparative advantage indexes. Open Econ. Rev. 33, 477–503. https://doi.org/10.1007/s11079-021-09636-4.

Ding, Y.-L., 2020. Study on the evolution characteristics of international nickel ores trade from perspective of complex networks. E3S Web of Conferences, 02050. https://doi.org/10.1051/e3sconf/202014302050, 143.

Dong, X., An, F., Dong, Z., Wang, Z., Jiang, M., Yang, P., An, H., 2021. Optimization of the international nickel ore trade network. Resour. Policy 70, 101978. https://doi.org/10.1016/j.resourpol.2020.101978.

Dou, S., Zhu, Y., Liu, J., Xu, D., 2024. The power of mineral: shock of the global supply chain from resource nationalism. World Dev. 184, 106758. https://doi.org/10.1016/j.worlddev.2024.106758.

Fan, Y., Ren, S., Cai, H., Cui, X., 2014. The state's role and position in international trade: a complex network perspective. Econ. Modell. 39, 71–81. https://doi.org/10.1016/j.econmod.2014.02.027.

Gönçer-Demiral, D., İnce-Yenilmez, M., 2022. Network analysis of international export pattern. Soc. Netw. Anal. Min. 12, 156. https://doi.org/10.1007/s13278-022-00984-8.

Jia, X., Liu, C., Li, T., Liu, J., Wang, X., 2024. The impact of country risk on the nickel supply chain: based on complex network and panel regression analysis. Front. Earth Sci. 12, 1487521. https://doi.org/10.3389/feart.2024.1487521.

Kali, R., Reyes, J., 2007. The architecture of globalization: a network approach to international economic integration. J. Int. Bus. Stud. 38, 595–620. https://doi.org/10.1057/palgrave.jibs.8400286.

Khalil, S.B., Broughel, A., 2025. Stainless success, battery lag: evaluation of Indonesia's resource nationalism in nickel. Extr. Ind. Soc. 23, 101677. https://doi.org/10.1016/j.exis.2025.101677.

Kocourek, A., 2015. Structural changes in comparative advantages of the BRICS. Proced. Soc. Behav. Sci. 172, 10–17. https://doi.org/10.1016/j.sbspro.2015.01.329.

Ma, Y., Wang, M., Li, X., 2022. Analysis of the characteristics and stability of the global complex nickel ore trade network. Resour. Policy 79, 103089. https://doi.org/10.1016/j.resourpol.2022.103089.

Mudd, G.M., Jowitt, S.M., 2022. The new century for nickel resources, reserves and mining: reassessing the sustainability of the devil's metal. Econ. Geol. 117 (8), 1961–1983. https://doi.org/10.5382/econgeo.4950.

Patunru, A.A., 2023. Trade policy in Indonesia: between ambivalence, pragmatism and nationalism. Bull.Indonesian Econ. Stud. 59 (3), 311–340. https://doi.org/10.1080/00074918.2023.2282821.

Ran, Y., Yi, J., Si, W., Small, M., Shang, K., 2025. Machine learning informed by micro- and mesoscopic statistical physics methods for community detection. Chaos: Interdiscipl. J. Nonlinear Sci. 35 (7). https://doi.org/10.48550/arXiv.2504.13538.

Sajedianfard, N., Hadian, E., Samadi, A.H., Dehghan Shabani, Z., Sarkar, S., Robinson, P. A., 2021. Quantitative analysis of trade networks: data and robustness. Appl. Network Sci. 6, 46. https://doi.org/10.1007/s41109-021-00386-3.

Seok, H., Nam, Y., 2022. A social network analysis of international creative goods flow. Sustainability 14 (8), 4463. https://doi.org/10.3390/su14084463.

Shi, J., Zhang, C., Chen, W.-Q., 2021. The expansion and shrinkage of the international trade network of plastic wastes affected by China's waste management policies. Sustain. Prod. Consum. 25, 187–197. https://doi.org/10.1016/j.spc.2020.08.005.

Sun, X., Jiao, Y., Hao, H., Liu, Z., Zhao, F., 2024. Physical and monetary characterization of the global nickel flow network. Resour. Policy 94, 105130. https://doi.org/10.1016/j.resourpol.2024.105130.

Suryanto, E., 2022. Apakah nikel Indonesia memiliki keunggulan daya saing di pasar internasional? Ecoplan 5 (2), 110–119. https://doi.org/10.20527/ecoplan.v5i2.506.

Tajoli, L., Airoldi, F., Piccardi, C., 2021. The network of international trade in services. Appl.Network Sci. 6, 68. https://doi.org/10.1007/s41109-021-00407-1.

USGS, 2022. Mineral commodity summaries 2022: nickel. U.S. Geological Survey, pp. 114–115. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nickel.pdf. (Accessed 7 April 2025).

Wang, X., Wang, A., Zhu, D., 2022. Simulation analysis of supply crisis propagation based on global nickel industry chain. Front. Energy Res. 10, 919510. https://doi.org/10.3389/fenrg.2022.919510.

Warburton, E., 2024. Nationalist enclaves: industrialising the critical mineral boom in Indonesia. Extr. Ind. Soc. 20, 101564. https://doi.org/10.1016/j.exis.2024.101564.

Xia, J., Wang, Y., Lin, Y., Yang, H., Li, S., 2018. Alliance formation in the midst of market and network: insights from resource dependence and network perspectives. J. Manag. 44 (5), 1899–1925. https://doi.org/10.1177/0149206316630379.

Yang, Q., Dong, Z., Zhang, Y., Li, M., Liang, Z., Ding, C., 2021. Who will establish new trade relations? Looking for potential relationships in international nickel trade. Sustainability 13 (21), 11681. https://doi.org/10.3390/su132111681.

Yu, Y., Ma, D., Qian, Y., 2023. A resilience measure for the international nickel trade network. Resour. Policy 86, 104296. https://doi.org/10.1016/j.resourpol.2023.104296.

Zeng, X., Xu, M., Li, J., 2018. Examining the sustainability of China's nickel supply: 1950–2050. Resour. Conserv. Recycl. 139, 188–193. https://doi.org/10.1016/j.resconrec.2018.08.011.

Zhang, D., Sun, Z., 2022. Comparative advantage of agricultural trade in countries along the Belt and Road and China and its dynamic evolution characteristics. Foods 11 (21), 3401. https://doi.org/10.3390/foods11213401.

Zheng, S., Zhou, X., Zhao, P., Xing, W., Han, Y., Hao, H., Luo, W., 2022. Impact of countries' role on trade prices from a nickel chain perspective: based on complex network and panel regression analysis. Resour. Policy 78, 102930. https://doi.org/10.1016/j.resourpol.2022.102930.