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Mining industry networks influence the diffusion of innovations in the battery minerals sector

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Abstract

The shift toward decarbonisation in the transportation sector, primarily through the adoption of electric vehicles (EVs), has significantly increased the demand for battery minerals such as lithium, nickel, and manganese. This, in turn, leads to the development of new mining operations and the expansion of existing ones. Recognising the reputational risks associated with the mining industry, and the supply risks associated with transnational multi-layered supply chains, EV manufacturers are intensifying their focus on sustainability-focused innovations and responsible sourcing. However, the industry dynamics of information flows driving the adoption of these innovations and their impact on the supply chain remain largely unexplored. This study aims to address this gap by analysing the diffusion of innovations within the global mining industry, particularly in the context of selected battery mineral supply chains. Employing network theory, we compiled datasets and constructed comprehensive networks of national and international mining industry associations and their affiliated companies. We focused on the top-producing countries for lithium, nickel, and manganese, utilising network-based diffusion algorithms to model the channels potentially available for the dissemination of innovations. Our findings reveal a pronounced transnational character in these networks, with notable isolations. The inclusion of international leadership organisations in the network analysis highlighted their potential role in facilitating faster information dissemination among transnational companies. These results provide critical insights into the mechanisms of innovation diffusion in mining supply chains and underscore the significance of industry associations in influencing sustainability practices. This study contributes to a deeper understanding of the network dynamics that govern the adoption of sustainability innovations in the mining sector, offering a basis for further research.

1. Introduction

The complex environmental challenges faced in the 21st century, including environmental pollution and threats to human health, ecosystem degradation, and limited resource availability, pose a significant threat to human life and prosperity [1]. Transport systems are some of the most environmentally impactful human activities, being material-intensive and still reliant on fossil fuels, accounting for roughly one quarter of all Greenhouse gas (GHG) emissions globally [2]. Although there has been significant discussion of minimising car dependency, investing in high-quality public transport, and reducing travel overall, the remaining vehicular fleet will require significant electrification. Therefore, massive deployment of all available low-emission enabling technologies, such as electric vehicles (EVs), will be required if a net-zero goal is to be achieved in 2050 [3].

On a global level, international treaties such as the Kyoto Protocol and UN resolutions, including Agenda 30 that defined the UN Sustainable Development Goals, contributed to the integration of renewable energy generation and clean energy storage across sectors [4]. On a national level, several countries have already planned to phase out or ban sales of petrol- and diesel-powered cars [5]. To achieve the massive shift towards renewable energy generation and clean energy storage within the sector, we will see increased demand for mineral commodities such as lithium, cobalt, nickel, and rare earth elements. Most of these metals have only previously been mined in modest amounts, increasing their forecast demand [6]. This requires global manufacturers to rely on complex supply chains, with complex embedded potential for environmental and social impacts. For instance, one of the top-three EV battery manufacturers, Panasonic, has more than 10 000 suppliers worldwide [7].

Hence, there have been significant concerns regarding the supply of battery minerals. For instance, concerns related to lithium have arisen due to the potential for extraction of lithium-rich brines in the Lithium Triangle (Argentina, Bolivia, and Chile) to contaminate water resources, alter regional hydrology and potentially lead to water shortages and ecosystem impacts [8]. Similarly, nickel mining poses substantial environmental challenges including high GHG emissions from energy-intensive processing [9], risks associated with tailings waste management [10], and biodiversity loss in sensitive ecosystems [11] Therefore, as downstream companies, such as battery manufacturers, and consumer-facing EV manufacturers, become more preoccupied with reputational risks associated with environmental catastrophes and human rights violations, approaches to supplier engagement are becoming more standardised—Mines, smelters, refiners, and battery assemblers are being scrutinised. Mining companies are being pushed to improve their raw materials extraction and processing and are being influenced by institutional investors, regulatory entities, and civil society to engage in detailed reporting [12].

The concerns on sustainability impacts associated with mining have given rise to industry sector-specific voluntary initiatives [13], as a means of industry self-regulation, with more than 50 voluntary initiatives applicable to the mineral sector [14]. These initiatives vary widely in their adoption methods, with one notable approach being the engagement with national industry platforms, exemplified by the Towards Sustainable Mining (TSM) initiative, now implemented in 13 countries. The TSM approach involves including a national industry platform to disseminate the standards across the companies operating in that country (not limited to mining but involved in the sector). This approach aims to enhance operational quality and public acceptance of mining activities [12].

Recent studies have underscored the importance of a network-centric approach to better understand and manage these supply risks [15, 16]. This shift in perspective necessitates more nuanced and comprehensive analyses of supply chain networks. In this study, we compiled detailed datasets of mining sector industry associations and their constituent member companies. Using this, we constructed a network representation of the sector and applied various network-based analysis to understand the potential relative rate of information or voluntary sustainability initiative, based upon different assumed network topologies and first-mover/seed nodes. This allows us to assess the potential influence that transnational networks have, through information flows, into being vectors of influence to the adoption of sustainability innovations at a mine-site level. In this study, we define innovation as operational, technological, or organisational changes that improve sustainability outcomes at mine sites. Specifically, we focus on eco-innovation practices that reduce environmental impacts, such as emissions, water use, and land disturbance [17]. Examples include the adoption of renewable energy systems, enhanced water recycling, or adherence to voluntary sustainability initiatives and certification schemes [12]. We focus exclusively on eco-innovations for two reasons. First, environmental practices are typically codified in industry guidelines and voluntary standards (e.g. TSM's tailings management protocol [18], International Council on Mining and Metals (ICMM's) water reporting guidelines [19], and IRMA's standard for responsible mining: GHG emissions [20]), which we assume can be diffused through transnational industry networks. Second, environmental performance can be quantified more precisely, and its improvement can often be modelled from well-specified technical or process changes (e.g. energy intensity, water-use factors). Social-impact innovations (e.g. labour-rights agreements), by contrast, evolve over longer timescales and are prone to systemic, sometimes unintended, consequences that introduce substantial heterogeneity that would not be covered by our methodological approach. Capturing those dynamics would require a different modelling framework and data set beyond the scope of our network-centric analysis.

2. Research context

2.1. Network dynamics and sustainability reporting in global mining supply chains

Global large-scale mining supply chains can be described as complex systems comprised of integrated facilities employing varied production techniques and being geographically distributed, dealing with a range of stakeholders, including governments, local communities, and downstream manufacturers, while also managing environmental and social footprints [21]. These operations are geographically dispersed, working in coordination, linked together by materials, information and financial flows, which can traverse the supply chain in both forward and backward directions [22]. With decentralised global steps within supply chains being supervised by a range of distinct stakeholders with unique managerial philosophies [23], decision-making within supply chains can be far from optimal. Pimentel *et al* [21] studied approaches for analysing mining *supply chains* overall sustainability citing that '*one of the most challenging changes in the way companies work with sustainable development is the shift of focus from their particular operations towards the improvement of the performance of their entire supply chains*', also mentioning that the integration of impact assessment methods, multi-criteria decision analysis and mathematical optimisation can be supportive of sustainable whole life-cycle design of mining networks [21].

Mining companies are increasingly faced with the challenge of meeting stringent requirements from downstream stakeholders in a highly price-sensitive market, while upholding their social license to operate. In response, these companies are turning to innovations that align with these objectives [24]. Eco-innovations play a pivotal role in this context, focusing on reducing the environmental footprint while maintaining economic competitiveness. Within the extractive industries, eco-innovations are defined as innovations that reduce the environmental impact or the use of resources [17], through the implementation of a novel process or technology, being '*less environmentally harmful than the use of relevant alternatives*' [25]. Examples in the mining industry include offsetting fossil fuels with solar energy [26], fleet electrification, water recycling and freshwater use reduction [27], tailings co-disposal and recycling [28], and many more. While these have a positive impact in mitigating environmental impacts, it is important to note that they might also reduce costs to operate, reduce risks, and increase safety [29]. Such innovations are often aligned with standardised operational and reporting frameworks, enabling relatively easier cross-border transfer across mining companies operating internationally, and will be the focus of this work. In contrast, social innovations, such as Indigenous rights engagement, labour rights improvements, and community participation models, are highly context-specific, depending on localised regulatory frameworks, societal norms, and political negotiations.

The adoption of such eco-innovations by a mining company can take place through the involvement of several partners and is influenced by characteristics of the networks in which these partners operate [30]. Network relations are related to the formal reporting structure and formal and informal relationships among internal groups within a firm and between a firm and its industrial environment [31], with external cooperation being an important driver to eco-innovations [32]. Nuss *et al* made a noteworthy contribution in bringing network theory to the analysis of mineral supply chains [33]. In their work, they have explored the assessment of supply chain risks using network analysis of product platforms, tracking the flow of materials from mineral extraction to end-use in final products (solar cells, turbine blades, batteries, and magnets). This study introduced network indicators and analysed mineral supply-chain risk with a network theory overlay, providing significant insights that have been considered in future studies covering other commodities. Additionally, van den Brink *et al* has done work in incorporating network theory into the analysis of Cobalt supply chain disruption risk, providing significant insights on the network characteristics of a particular commodity supply network [15]. Nonetheless, this work still described a notable gap in assessing the linkages between companies from a network standpoint.

2.2. Diffusion of innovations and networks

The notion of '*diffusion of innovation*', initially introduced in 1962 by Everett Rogers, has significantly influenced our understanding of the interactions between entities leading the adoption of innovations [34]. Moreover, a range of studies have been conducted around the innovation dynamics of networks, including eco-innovation through inter-firm networks [35], the influence of trust and distrust in the system [36], and many more. The adoption of eco-innovations holds uncertain value [37], and can be considered to be more complex than conventional market-driven innovation [38], requiring the overcoming of intra- and inter-organisational management challenges [39]. The role of networks and relationships in driving eco-innovation has been successfully demonstrated [40], as well as the concept that opinion leaders who have a higher influence on other agents and have strong weighted links to other agents are found to spread information faster and increase the rates of adoption over the network [41]. Moreover, more radical eco-innovations require greater internal and external firm resources, leading to higher thresholds for adoption and diffusion due to the lower incentives and pressures for their adoption [42].

Considering that learning involves exchanging information between actors and revising such opinions based on the opinions and behaviour of others [43], the influence of inter- and intra-firm relationships, either through a centralised association or not, should not be overlooked. Especially since the formation of collective opinions can be analysed under the lens of diffusion of innovation within a network structure [37]. Networks might shape how companies involved within this supply chain communicate, and how they form their opinions related to best practices, environmental and social reporting, and adoption of complex eco-innovations such as certifications, standards, and initiatives. The role of cross-industry collaborations as

Table 1. National mining industry associations in the leading nickel, lithium, and manganese producing countries. This table also includes international leadership associations and commodity-specific associations.

Country	National level mining industry association	Acronym	# of members
Australia	Minerals council of Australia	MCA	124
Argentina	Cámara Argentina de Empresarios Mineros	CAEM	151
Brazil	Instituto Brasileiro de Mineração	IBRAM	161
Canada	Mining Association of Canada	MAC	100
Chile	Sociedad Nacional de Minería de Chile	SONAMI	115[a]
Ghana	Ghana Chamber of Mines	GCM	95
Indonesia	Indonesia Mining Association	IMA	90
Philippines	Chamber of Mines of the Philippines	COMP	72
South Africa	Minerals Council South Africa	MCSA	77
International	International Council on Mining and Metals	ICMM	65
International	International Lithium Association	ILiA	68
International	International Manganese Institute	IMnI	123
International	Nickel Institute	NI	17

[a] For SONAMI, individuals have not been included (Personas Naturales and Honorarios).

a way to address due diligence in complex supply chains has been explored, and the role that Industry associations have in responding to their members 'needs to support shared learning has been analysed [44]. Moreover, it has been argued that mining industry associations are influential in developing standards and codes that shape the institutionalisation of corporate social responsibility practices [45].

Networks are naturally empirical, data-driven, and interdisciplinary with a high potential for economic, managerial, and societal impact. In the efforts to describe and detail the behaviour of a complex system containing hundreds, thousands, and maybe even millions of interacting components, this study aims to increase the body of work that looks at battery minerals supply chains from that standpoint. The identification and mapping of such networks is a necessary step towards the understanding of how eco-innovations might be disseminated.

3. Research objectives and methods

The main objective of this research is to conduct a network-based analysis aimed at clarifying the potential relative rate of information dissemination across several industry collaboration network topologies. With this analysis, we expect to better understand the potential for eco-innovations within the battery minerals sector. Because the structure and scope of these networks are shaped by the organisations that lead and participate in them, it is important to first identify the key national, international, and commodity-specific associations relevant to the sector. Table 1 presents this mapping, listing national mining industry associations in the leading nickel, lithium, and manganese producing countries, alongside major international leadership bodies and associations dedicated to specific commodities.

3.1. Selection of primary commodities and industry associations

Three primary commodities have been selected for this study due to their significance in the manufacturing process of lithium-ion battery cathodes: Lithium, nickel, and manganese. Our preliminary analysis utilised the 2020 data from the British Geological Survey's (BGS) world mineral statistics database [46] to identify the leading producing countries for these commodities. This dataset has been cross-referenced against the nickel, lithium, and manganese *Mineral Commodity Summaries* from the United States Geological Survey [47–49]. This assessment yielded a list of 14 top-producing countries, which are detailed in table 1. The primary producers for each of these three commodities are depicted in figure 1. For lithium, we used the BGS 'Lithium minerals (Li content)' parameter, which reports lithium production in terms of contained elemental lithium (t Li), allowing comparability across different mineral sources and processing routes. Where applicable, values from carbonate production were added to account for brine-based production, notably in Argentina and Chile.

For each of these top producers, we identified their respective national-level mining industry association, with one association being selected per country, with these are detailed in table 1. A criterion for the inclusion of an industry association was the availability of a public list of member companies. Public information was notably absent for China, Russia, Gabon, India, and New Caledonia. Two national-level industry associations were considered for China. The *Global Mining Association of China* website was accessed, but no membership data was found. Similarly, The *China Chamber of Commerce of Metals, Minerals and Chemicals Importers and*

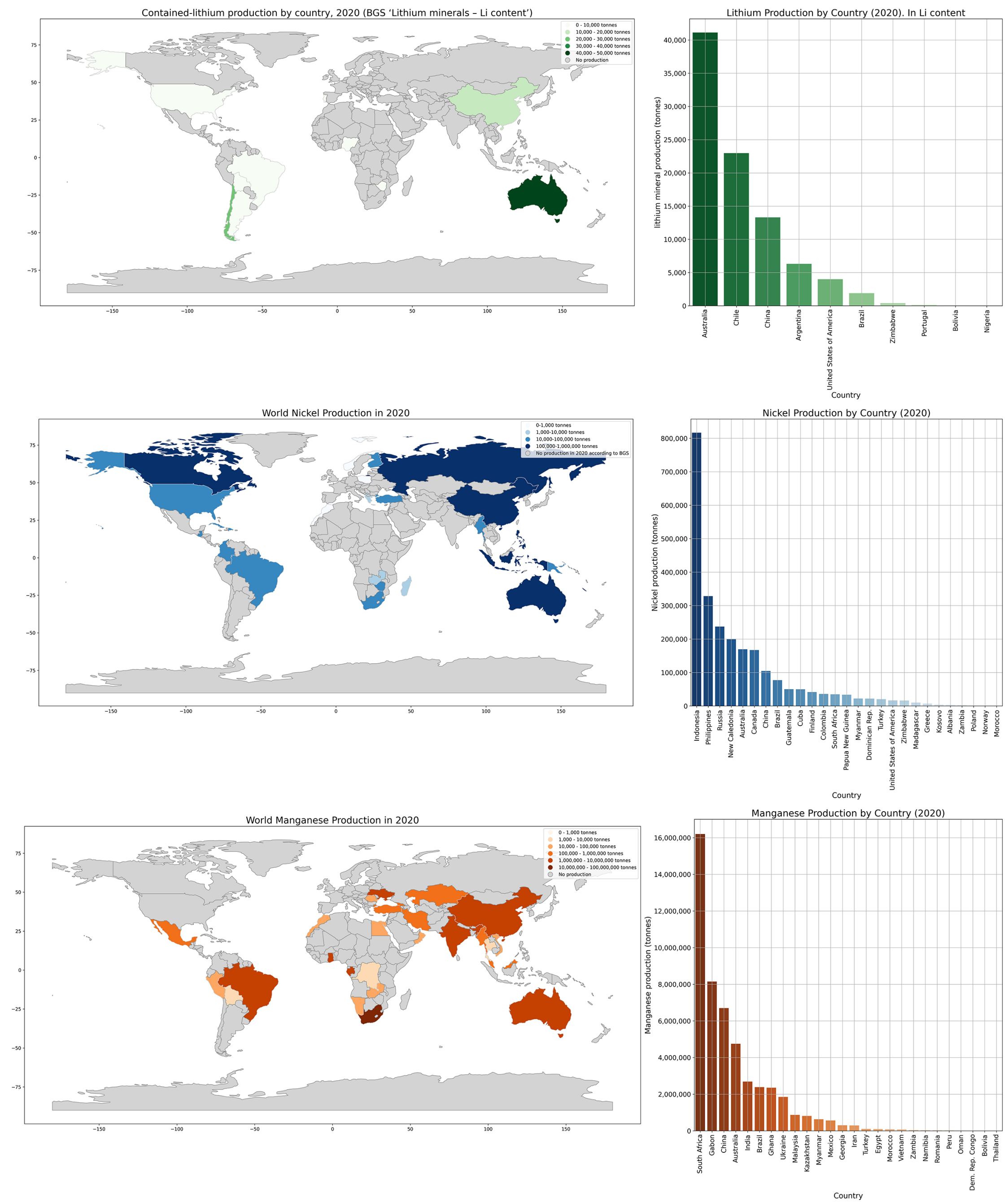

Figure 1. Identification of top producing countries of lithium, nickel, and manganese, based on 2020 data from the British geological survey's mineral commodity summaries. Panel a presents lithium production expressed as tonnes of contained elemental lithium (t Li). Panels b and c represent nickel and manganese production in gross metric tonnes, without transformation, as reported in the BGS database.

Exporters website had no public information on associated members. Importantly, Russia and China were significant producers of nickel in 2020, accounting for approximately 9.6% and 4.3% of global production, respectively. No significant mining industry association could be found for Russia and Gabon. For India, The Federation of Indian Mineral Industries has been considered, but no public data was available related to their members. As for New Caledonia, as an ultramarine territory of France, a national-level industry association representative of France was considered, but no public information was found on that matter.

In the case of the nine qualifying countries, we compiled an extensive list of operational members of their respective industry associations. These companies were systematically categorised based on their association membership, with a detailed collection of attributes for each. These attributes included the type of membership held, the specific industry sector of operation, and the commodities mined (when relevant), as described in figure 2.

In addition to the national industry bodies, we considered one international leadership association and three commodity-specific associations to assess their role in shaping the global network and its potential

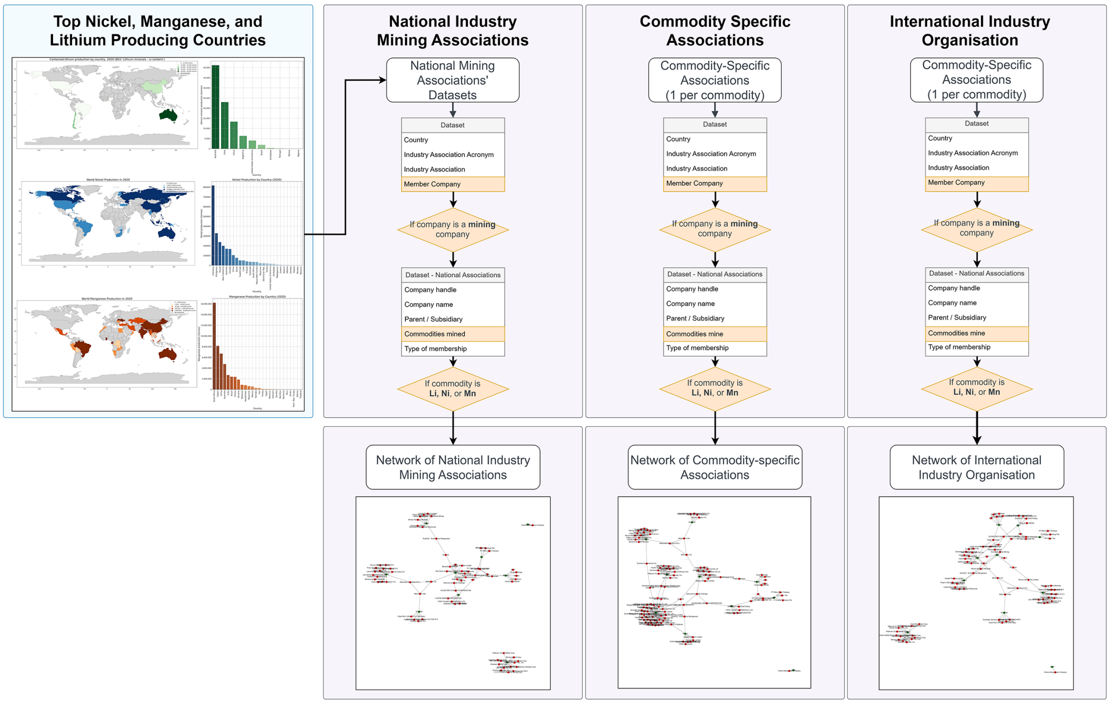

Figure 2. Graphical representation of data collection process and dataset creation of national and regional industry associations and company membership.

influence on adoption practices. These include the ICMM, the *International Lithium Association* (ILiA), the *International Manganese Institute* (IMnI), and the *Nickel Institute*. Membership in these associations is contingent upon a formal admission process and adherence to various performance commitments.

3.2. Standardisation of company names

In our methodology, we collected descriptive information for each company within the associations. This data comprised company names, locations of mining operations, and the commodities mined. These names were sourced from public documents, stock exchanges, press releases, and mining databases, noting that the format of these names was not standardised across sources. To standardise the company names, a four-step process was conducted. Step 1 included the removal of common corporate suffixes (e.g. S.A., PLC, Ltd, AG) from the names. A comprehensive list of the removed suffixes is available in the supplementary material. Subsequently, we manually corrected typographical errors and filled in missing values in the company names. We then applied the *Levenshtein distance* algorithm to assess the similarity between names. This measure identifies the minimum number of edits needed to transform one string into another, providing a quantitative basis for comparing string sequences. At last, another round of manual corrections was performed to ensure accuracy.

The *Levenshtein distance* is a method for measuring the difference between two sequences of strings (names, sentences, etc.), defined as the minimum number of edit operations to transform one string into another [50]. This algorithm is widely used in information theory to quantify the difference between two sequences, and therefore can be used to identify similarities between strings that should be the same but might be typed differently [51]. The distance (number of edits) between two strings S_1 and S_2 can be calculated and converted into a similarity measure (between 0.0 and 1.0) by using the formula:

$$\mathrm{sim}_{ld}(s_1, s_2) = 1.0 - \frac{\mathrm{dist}_{ld}(s_1, s_2)}{\max(|s_1|, |s_2|)}.$$

Each string from an association was compared against every string from every other association. This exhaustive comparison generated a unique dataset for each association, ensuring accurate matching. This process proved effective in identifying similarities, such as *JFE Mineral* and *JFE Mineral & Alloy* (this pair yielded a 91.5% match). Moreover, it was supportive of findings typos on the original datasets extracted from public information, with an example being the 97.5% match between *Sumitomo* (correct spelling) and *Sumimoto* (wrong spelling).

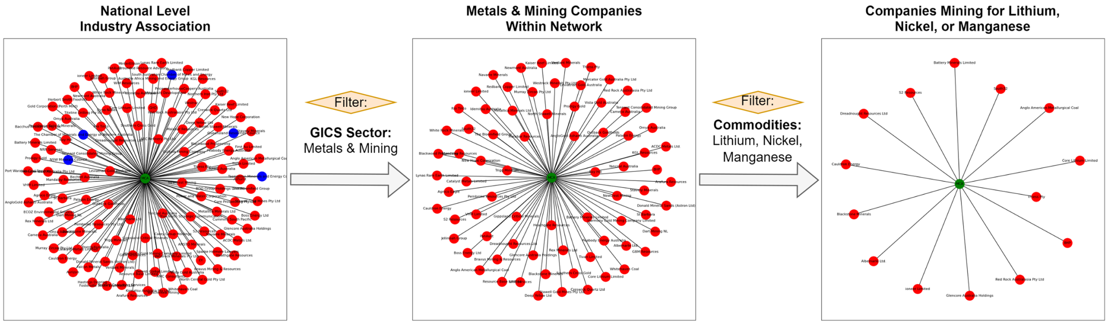

Figure 3. Initial network setup with industry associations at the centre and members connected to its central node. In red are overall members. In blue are other industry associations connected to the main industry association.

3.3. Network setup

We employed network theory to model the relationships between firms and industry associations within the mining sector. Our model consists of nodes and edges, where nodes represent entities such as organisations, individuals, or other units, and edges symbolise the connections between these nodes. This approach enables us to employ established network theory methodologies to examine the structural characteristics [52] and interfirm collaboration dynamics [53] within these networks. It is important to note that the network constructed is cross-sectional, based on publicly available association membership at a given point in time. Therefore, temporal dynamics such as changes in membership, firm exits or entries, and evolving relationships were not captured.

In our network-based framework, each national industry association is depicted as a core node with affiliated companies connected via edges, as visualised in figure 3. We further categorised each company according to its corresponding global industry classification standard (GICS) code. This categorisation facilitated an in-depth analysis of the entire network, with a specific focus on those entities within the *Metals & Mining* sector (GICS code 151040). For companies within the *Metals & Mining* sector, we added an additional attribute to their node representation, indicating the specific mineral commodities they have active mining operations or prospective projects. We further conducted extensive searches for each company in public databases to standardise their names and identify their parent companies. Companies sharing the same parent company were directly connected in our model.

3.4. Innovation diffusion modelling across networks

After applying appropriate filters for industry sector and selected battery commodities, we conducted the diffusion analysis over the networks. Initially, all the national-level industry associations have been consolidated as one global network, as showcased in figure 4 panel (a). This global network represents the collective influence of industry associations on the innovation adoption process in battery minerals mining companies. We utilised this unified network as the basis for our initial diffusion analysis. Following this analysis, we overlaid the networks built using the data from ICMM, ILiA, IMnI, and Nickel Institute onto our global network, as showcased in figure 4 panel (b), which depicts the overlay of ICMM over the national associations network. This additional step allowed us to assess how the inclusion of an influential international body modifies the potential diffusion dynamics.

Post-constructing the networks, we employed a two-tiered diffusion model to analyse the spread of innovations across the global network. This model was built upon two core algorithms:

(i) **Diffusion algorithm**: This algorithm initiates with each node in the network designated as *susceptible*. A selected *seed node*, representing an international industry association, is set to *'adopted'* status, signifying it is the initiator of the innovation. The diffusion process then unfolds iteratively, with each adopted node attempting to influence its susceptible neighbours based on a predetermined probability (*p-value*). Upon exerting its influence, the node transitions to an *immune* status, indicating its active phase in the diffusion process is complete. It neither adopts the innovation nor tries to influence adoption. The algorithm's output is the final count of nodes that have transitioned to the *immune* status, reflecting the total adoption spread. This can be observed in the following equation (1):

$$\text{Output} = \sum_{\{i=1\}}^{\{N\}} 1_{\{\text{status}(i)='\text{immune}'\}} \quad (1)$$

where:

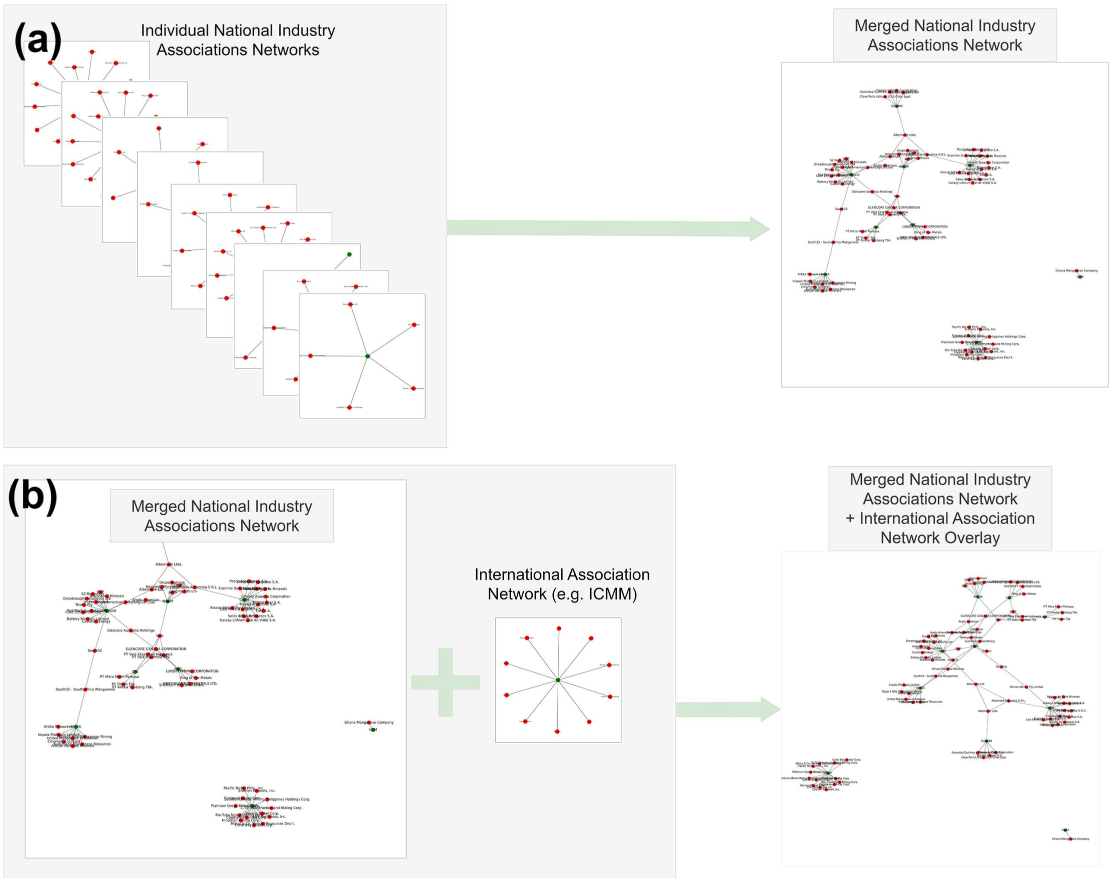

Figure 4. Construction of networks using the national level industry associations and ICMM. This construction has been done post filtering the companies for their industry sector (Metals & Mining) and commodity specific (lithium, nickel, and manganese). The same process utilised to generate panel (b) has been applied to ILiA, IMnI, and Nickel Institute.

N is the total number of nodes in the network.
$1_{\{.\}}$ is the indicator function, which is 1 if the condition inside the braces is true, and 0 otherwise.
status (i) represents the status of node i after the execution of the diffusion process.

(ii) **Network diffusion simulation**: Building upon the first algorithm, this simulation varies the *p-value* from 0.1 to 1.0, conducting 1000 iterations for each value. For each iteration and *p-value*, the total number of adopted nodes is tallied. The process is repeated for each industry association as the *seed node*, allowing us to assess how different starting points impact the diffusion's effectiveness. The results are then averaged for each *p-value*, creating a results dataset that compares the diffusion's efficiency across various industry organisations as the *seed node*. This process is detailed in the following equation (2).

$$R(p) = \frac{1}{1000 \times n} \sum_{\{i=1\}}^{1000} \sum_{\{j=1\}}^{n} A(p,j,i) \tag{2}$$

where:
p varies from 0.1 to 1.0.
$n = 10$, being the number of industry associations analysed
$A(p, j, i)$ is the number of adopted nodes for the ith iteration, with industry association j as the seed node, and at p-value p.

By employing this approach, our study systematically explores how variations in starting conditions and probability thresholds affect the diffusion of innovations within the network. The integration of these algorithms, executed via the NetworkX [54] and Pandas [55] Python libraries, provided a robust framework for our analysis, enabling a detailed exploration of network dynamics and the influence of industry associations on the propagation of innovations.

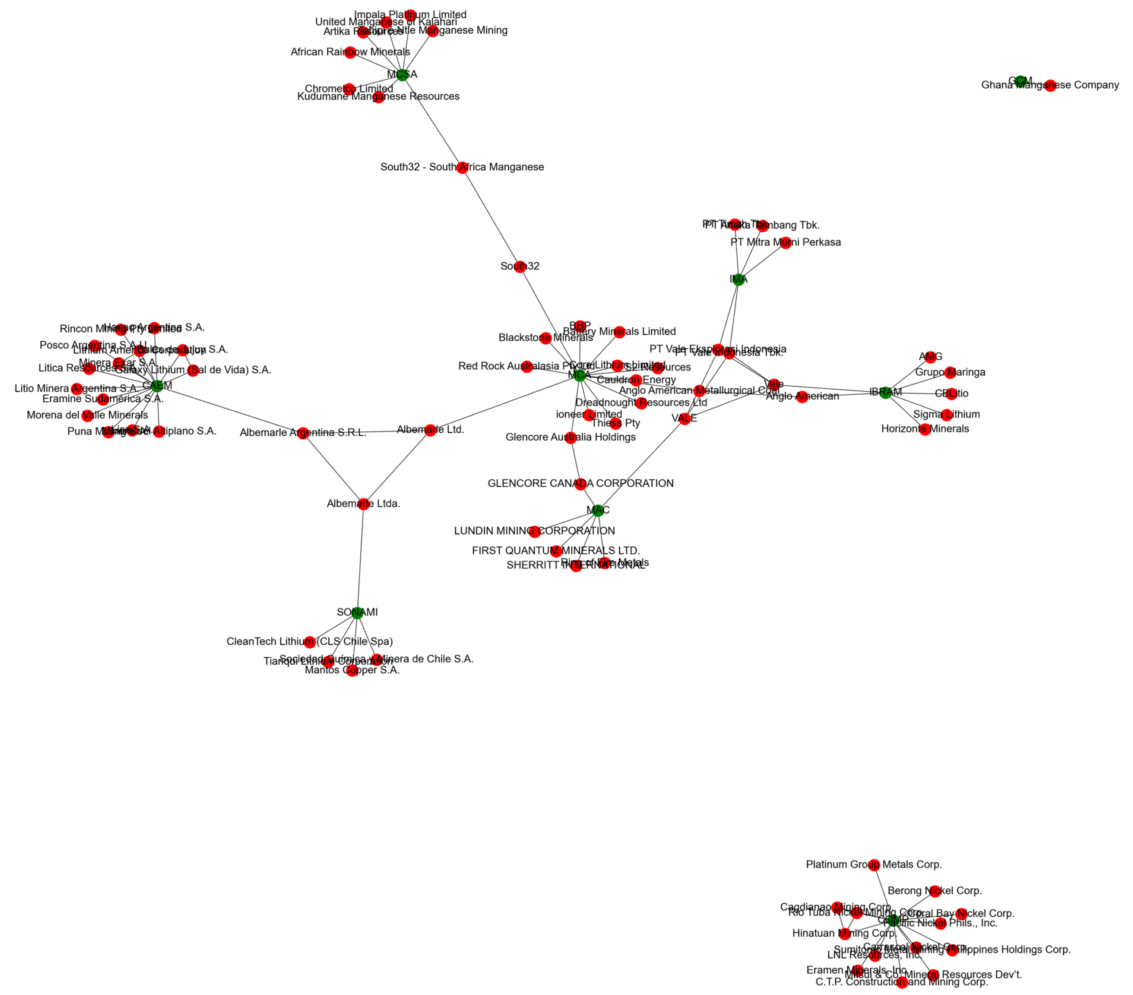

Figure 5. Global network of industry associations involved with metals & mining companies mining for lithium, nickel, and manganese. Not inclusive of ICMM. Top producing countries such as China, Gabon, New Caledonia, Russia, and India have not been covered due to a lack of publicly available data on industry association members.

It is imperative to describe that this process assumes a *heterogeneous population*, which is not representative of our sample, but is effective in drawing a baseline. Recognising the absence of firm-level attributes such as company size, ownership structure, and innovation readiness, we adopted a probabilistic simulation strategy by systematically varying the probability of adoption (p-value) from 0.0 to 1.0 in steps of 0.1, with 1,000 iterations conducted at each value. Rather than aiming to predict absolute adoption rates, this approach enables the exploration of a range of diffusion behaviours under varying adoption scenarios. This approach allows us to compare the relative diffusion efficiencies between different network configurations, despite not explicitly modelling firm-level heterogeneity.

4. Results

4.1. National-level industry associations

The network built using the nodes and edges extracted from the national industry associations can be seen in figure 5, with an overlay of the geographical position of the nodes in figure 6 similar figures for all the other networks can be found in the supplementary material. The transnational nature of the network seems evident, with notable isolations happening in the Ghana Chamber of Mines (GCM) and the Chamber of Mines of the Philippines (COMP).

Our diffusion routine allowed an innovation to travel along the following pathways:

1. **Intra-association pathway**: Once a seed node (industry association) adopts, the innovation reaches every other member of that same association through their shared hub connection.
2. **Cross-association bridging pathway**: Some companies in our dataset hold memberships in two or more associations. When any one of these firms adopts, it immediately exposes the secondary association's entire membership to the innovation, greatly shortening path length.

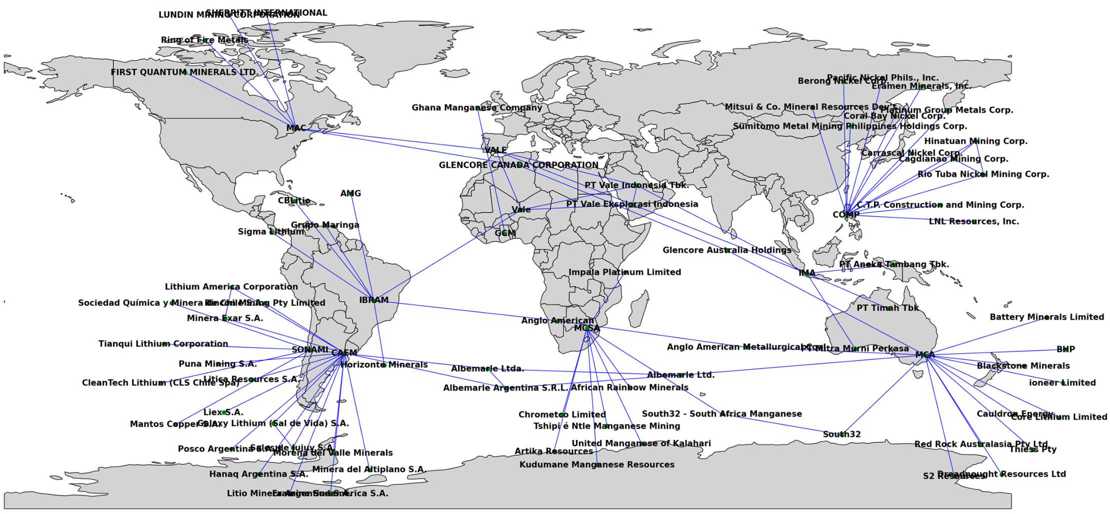

Figure 6. Global network of industry associations involved with metals & mining companies mining for lithium, nickel, and manganese. Not inclusive of ICMM. Top producing countries such as China, Gabon, New Caledonia, Russia, and India have not been covered due to a lack of publicly available data on industry association members.

3. **Parent-subsidiary pathway**: Subsidiaries share a common parent company. Adoption by one subsidiary gives its sibling an independent chance (p) to adopt, after which that sibling can relay the innovation into every association to which it belongs.

Upon execution of the two-tiered diffusion model (detailed in section 3.4.), the results of the diffusion across the global network (only inclusive of national industry associations) can be seen in figure 7 and are presented on table 2. For the *national associations only*, a total of 5 companies influenced the second pathway of adoption (cross-association bridging pathway), showcasing limited potential for this pathway is weak unless international associations are overlaid. Moreover, 17 parent-subsidiary pathways were present. Some initial perceptions showcase the isolation of the GCM and the COMP, indicating potential barriers in transnational information exchange among these companies. The results also provide insights into how certain industry associations facilitate information diffusion among their member companies to varying degrees.

4.2. Inclusion of international industry associations

Further, when we incorporated the international industry associations (ICMM, ILiA, IMnI, and NI) into the network, as shown in figure 8. We can notice that there was a noticeable upward shift in the diffusion curve. This suggests that the involvement of influential organisations might positively impact the speed at which information travels among transnational companies within the network. These findings imply that the presence of prominent international bodies can enhance the dissemination of information across companies that operate globally.

4.3. Impact of seed selection on innovation pathways across diverse networks

Finally, to explore how various seeds of network-diffused innovation influence diverse innovation pathways, we applied the diffusion algorithm across different networks (either the combination of national industry associations, or the overlaid networks with the international associations), keeping the same national industry association (e.g. from Australia, or Canada). The results of this analysis are presented in figure 9.

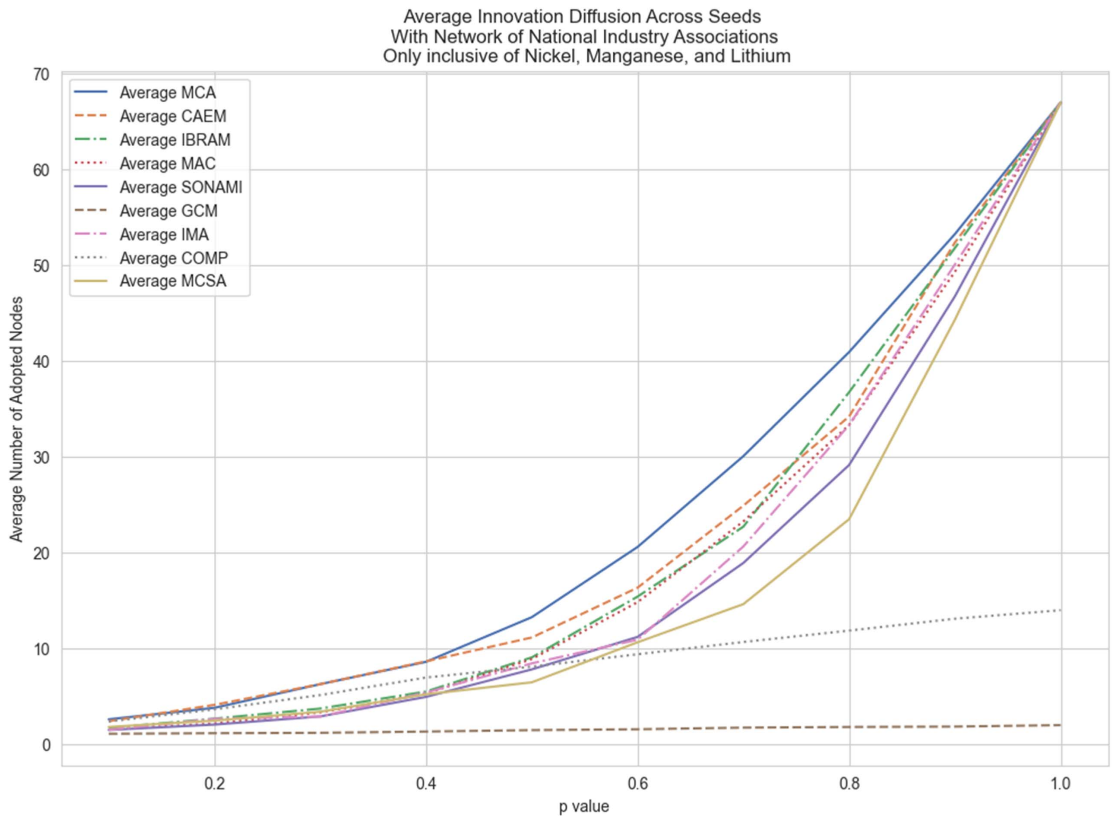

Figure 7. Tallied average results from the two-tiered diffusion model applied to the global industry association network. Limited to Metals & Mining industry and commodity-specific to lithium, nickel, and manganese.

Table 2. Structural capacity of diffusion pathways across network variants.

Network variant	Pathway 1 (Mean members)	Pathway 2 (Bridge companies)	Pathway 3 (Subsidiary pairs)
National associations only	8.2	5	17
ICMM Overlay	8.4	6	20
ILiA Overlay	10	13	29
NI Overlay	8.7	9	29
IMnI Overlay	11.5	8	24

5. Conclusion

5.1. Key insights and implications

Emphasising network-based diffusion analysis, we selected lithium, nickel, and manganese as primary commodities due to their pivotal role in lithium-ion battery cathode production and analysed the information diffusion across companies operating transnationally and being members of national industry mining associations, leading to the unveiling of potentially influential actors. The findings resonate with van den Brink's identified research gap related to firm-oriented network analyses in mining supply chains [15]. By focusing on the firm level, our study underscores the role of industry associations in mediating the diffusion of eco-innovations and highlights the impact of international bodies in enhancing global connectivity.

This study not only contributes to our understanding of network dynamics in mining but also provides a framework for future research to further explore firm-specific networks and their influence on sustainability practices in the sector. A fundamental aspect that must be further analysed is the association-to-association relationship and sphere of influence. The case of the GCM, an association member of the ICMM, is particularly noteworthy. While GCM lacks transnational firm connections facilitating outbound and inbound information flows, it maintains a direct connection to ICMM (As of February 2024, GCM is a member of ICMM [56]). Our results unveiled a distinct transnational nature of the network, with isolations like the GCM and the COMP highlighting potential information flow barriers. The inclusion of the ICMM in the network revealed an upward shift in the diffusion curve, suggesting that such influential bodies can

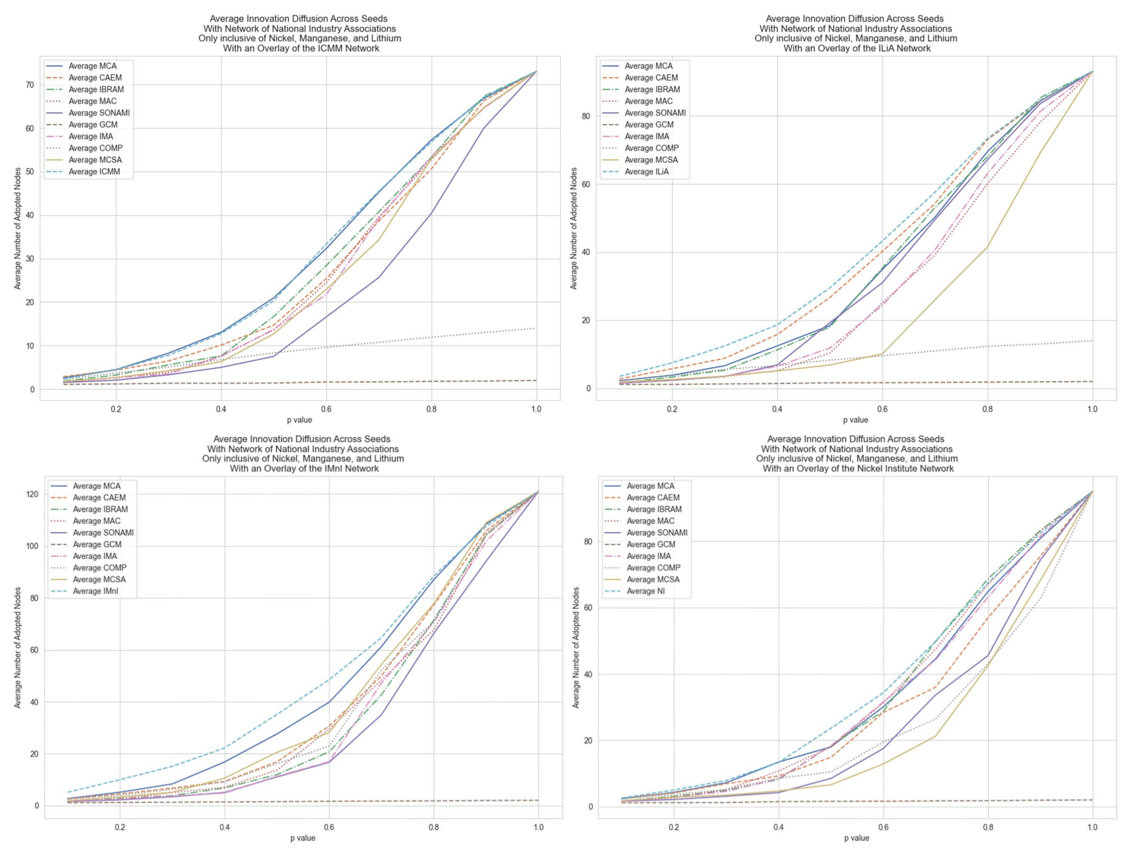

Figure 8. Tallied average results from the two-tiered diffusion model applied to the global industry association network, inclusive of the international collaboration networks. Limited to metals & mining industry and commodity-specific to lithium, nickel, and manganese. The upward shift reflects the greater prevalence of multi-membership bridges and the reduction in average path length when international associations are present.

significantly accelerate information exchange among transnational companies. Moreover, the inclusion of commodity-specific networks such as the ILiA, *the* IMnI, and the *Nickel Institute* proved fundamental to help bridge the gap across national borders. The proactive stance of these associations towards fostering innovation and change could have a profound impact on the long-term sustainability outcomes in the sector.

In the national-association network alone, an innovation seeded in a single association can immediately reach, on average, eight member companies—the maximum reach of the intra-association (Pathway 1) mechanism. However, only five firms in that baseline graph hold multiple association memberships, and just seventeen unordered subsidiary pairs share pathways to information flow. Consequently, the cross-association (Pathway 2) and parent-subsidiary (Pathway 3) channels are weak, and cumulative adoption flattens quickly. By looking at table 2 and figure 8, we can see that overlaying international organisations alters the structure proactively. Adding ICMM, ILiA, IMnI, or the Nickel Institute raises the number of bridge firms to 6–13 and increases subsidiary connections to 20–29. These additional conduits shorten the average network path length and elevate international hubs' betweenness-centrality scores, producing the steeper diffusion curves observed in figure 8. The results suggest that international associations may accelerate the propagation of environmental innovations by multiplying cross-cluster links and connecting otherwise distant parts of the network.

5.2. Limitations and future work

One important limitation of this work is that we assumed a *heterogeneous population* within our network (the *p-values* were varied but held the same across companies for a given diffusion round). To account for the unknown firm-level adoption behaviours, we implemented a systematic variation of the diffusion probability (*p*-value) across the full range from 0.0 to 1.0, with 1,000 iterations per step. This allowed us to generate a robust comparative baseline across different network structures, rather than relying on a single, potentially unrealistic assumption of adoption likelihood. While this approach cannot fully substitute for firm-specific diffusion modelling, it provides valuable insights into the relative capacities of industry association networks to facilitate innovation spread. Future studies could refine this approach by linking probability thresholds to firm characteristics such as size, ownership, or historical innovation behaviour. Finally, we acknowledge that,

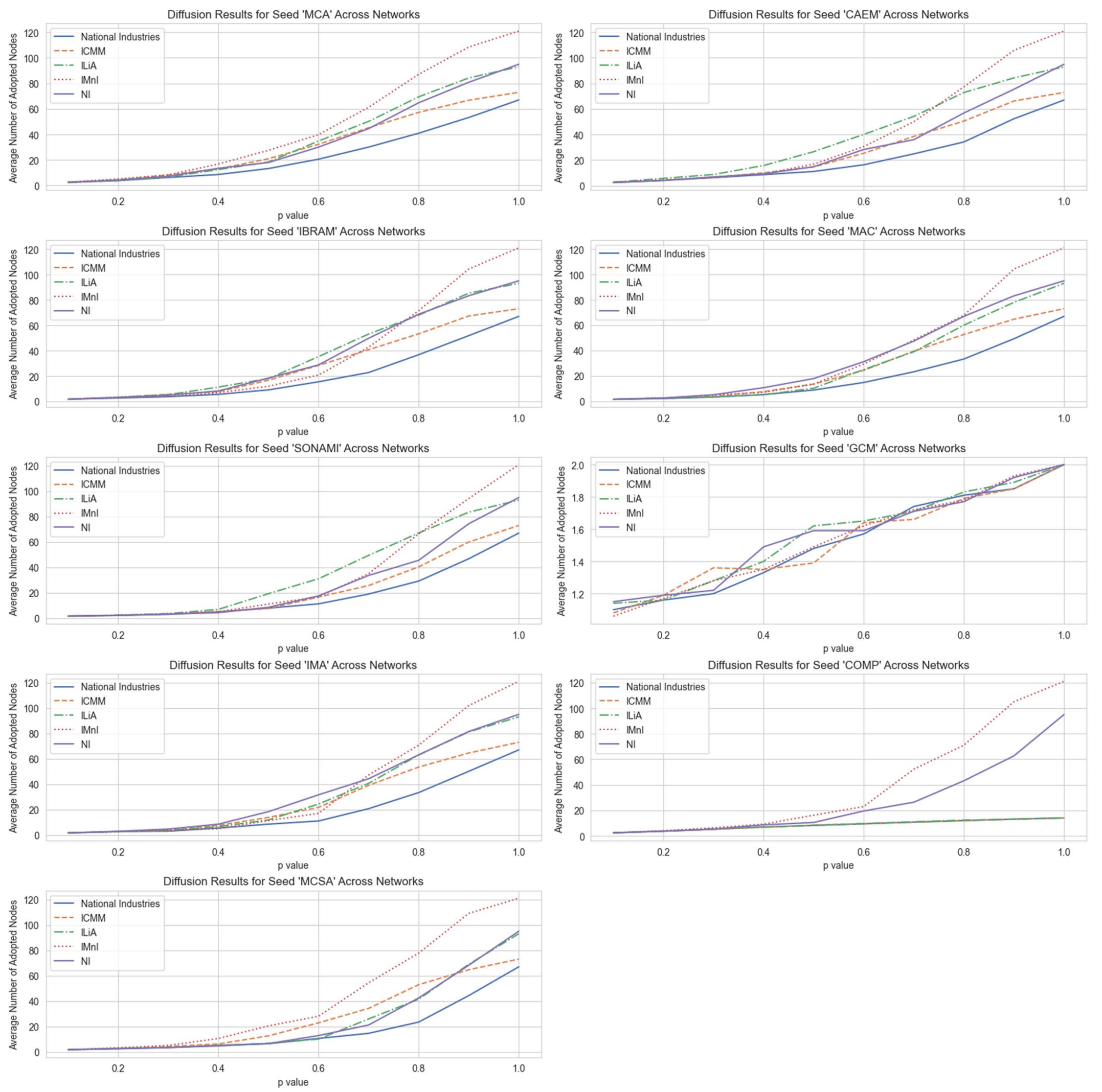

Figure 9. Tallied average results from the two-tiered diffusion model applied to distinct networks and keeping the seed of the diffusion process stable. Each graph depicts the same process for different starting national industry associations.

by restricting our quantitative analysis to eco-innovations, we do not capture the more heterogeneous diffusion dynamics of social-impact innovations. Future studies employing mixed-methods or longitudinal case-study designs will be required to address this complementary, and often overlooked, dimension of sustainability. Moreover, future studies could benefit from understanding and exploring the distinction between pathways of innovation adoption (e.g. employee inter-firm mobility). The relative importance of different pathways has not been assessed, and it may be possible that other pathways may be more influential than corporate memberships.

In future studies, a more intricate exploration of the network could be undertaken by incorporating an analysis of overlaid industry leadership organisations that are product-oriented, such as the global battery alliance [57]. This could be theoretically associated with the understanding of how such an organisation might help bridge the gap between commodities' expertise towards a product-oriented approach. The mechanisms by which previous eco-innovations have spread, such as TSM or comparable schemes, could also be assessed as case studies to understand how industry associations and their member companies communicate and coordinate to drive innovation in the sector. Moreover, future work could incorporate quantitative measures of innovation adoption to construct a more robust and intricate picture of the network's architecture and its capacity for innovation diffusion. This approach will not only refine our current understanding but also provide a scaffold for developing more effective strategies for managing and directing the flow of innovation within the industry.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15393296.

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