

Analyzing Research Collaboration Trends in NCM Batteries Using Bibliometric Analysis

Ho-Yeol Yoon, Jinseo Lee, Hochull Choe*

National Strategic Technology Division, Korea Research Institute of Chemical Technology (KRICT), Daejeon, SOUTH KOREA.

ABSTRACT

Objectives: East Asian countries-notably South Korea, China and Japan-have achieved excellent research outcomes in this domain. This study examined the evolving research landscape of Nickel Cobalt Manganese (NCM) batteries, driven by their widespread application in diverse fields, particularly those of electric vehicles and energy storage. **Research Design and Methods:** Employing bibliometric techniques, we conducted a comprehensive analysis on NCM battery-related research papers retrieved from the Web of Science databases. Our investigation spanned publication trends, authorship patterns and citation networks, providing valuable insights into thematic content and collaborative dynamics. **Findings:** Our findings suggests that East Asia-particularly China-is likely to continue leading in NCM battery research. However, East Asian countries should focus on collaborations to further innovate. The findings offer a nuanced understanding of the current state of NCM battery research and elucidate the key patterns and collaborative networks. We systematically identified areas of emphasis and potential avenues for future research. **Implications and Recommendations:** This study could facilitate the establishment of effective collaborative strategies in the field of NCM batteries, which could have considerable implications for scientists, policymakers and industry professionals. As NCM batteries are used in a range of applications, a more granular analysis in future should focus on specific applications to yield more insightful results.

Keywords: Nickel cobalt manganese battery, Secondary battery, Research collaboration trends, Bibliometrics.

Correspondence:

Hochull Choe

National Strategic Technology Division,
Korea Research Institute of Chemical
Technology (KRICT), Daejeon,
SOUTH KOREA.

Email: hchoe@kRICT.re.kr

ORCID: 0009-0004-1499-2925

Received: 04-02-2024;

Revised: 09-03-2024;

Accepted: 20-11-2024.

INTRODUCTION

With the advances in technology and rapid growth in Electric Vehicle (EV) sales, the secondary battery industry has grown rapidly.^[1] Batteries are ubiquitous in various fields, including industry, transportation, military and space exploration.^[2] As batteries are becoming safer and cheaper, their adoption is becoming increasingly diverse, ranging from small-scale electronics to large-scale energy storage applications. Consequently, the demand for secondary batteries is expected to reach 4,700 GWh and the global market for EV batteries is projected to grow to approximately \$400 billion by 2030.^[3]

Secondary batteries-commonly referred to as Lithium-Ion Batteries (LIBs)-are advantageous because of their long cycle life, low self-discharging rate, small size, light weight, rapid charging abilities and wide temperature range.^[4-6] LIBs can be categorized into three groups- lithium Nickel Cobalt Manganese oxide (NCM), lithium Nickel Cobalt Aluminum oxide (NCA) and

Lithium iron Phosphate (LFP) batteries,^[7] with NCM and LFP batteries most widely used in EVs and energy storage systems.^[8] Moreover, as realizing higher power densities has become an indispensable requirement for many battery applications, NCM batteries have been receiving increasing attention. Evolving from NCM 111 to NCM 811,^[9] battery technology has become one of the largest markets for nickel-rich ternary batteries.^[10] In 2022, NCM batteries remained the dominant battery chemistry with a market share of 60%, followed by LFP batteries, which is growing rapidly in China (with Tesla accounting for 30% of the LFP battery market share).^[11] Although the market share of LFP batteries is considerable, research and development of high-performance NCM batteries are being actively undertaken to improve their safety and stability and lower the manufacturing costs.^[12]

Many leading countries are making considerable efforts to achieve ascendancy in NCM battery technology-in particular, the competition between East Asian countries has become rather intense.^[13] These countries-primarily South Korea, China and Japan-are among the leading cathode producers, accounting for more than 90% of the secondary battery market.^[14] These countries, which dominate the global cathode production and secondary battery markets, are in a fierce race to innovate and secure patents, highlighting the geopolitical and economic stakes



DOI: 10.5530/jscires.20041152

Copyright Information :

Copyright Author (s) 2024 Distributed under
Creative Commons CC-BY 4.0

Publishing Partner : Manuscript Technomedia. [www.mstechnomedia.com]

involved. China, home to the largest EV market, has produced and used NCM batteries extensively, dominating the battery market.^[15] Considering South Korea and Japan accounts for a considerable share of the NCM battery market,^[16] Chinese businesses are actively pursuing NCM battery technology by filing patents and investing in the technology.^[17] To compete with South Korea and Japan, Chinese businesses are actively pursuing NCM battery technology by filing patents and investing in battery technologies. Moreover, South Korea and Japan account for a considerable share of the NCM battery market.^[16] South Korea-one of the leading battery suppliers-is eager to secure the secondary battery markets dominated by several conglomerates, such as LG Energy Solution and Samsung SDI.^[18] These companies focus on high-performance and high-energy-density NCM batteries based on superior technology and actively invest and participate in research and development. The South Korean government is planning to invest more than \$350 billion in the production of NCM batteries to take the initiative in the battery market.^[19] Another leading country, Japan, which accounts for approximately 20% of NCM battery patents, is focused on improving the performance of NCM batteries.^[20] In particular, National Innovation Systems (NIS) in East Asia are characterized by RandD investment and Science and Technology (SandT) Policies centred on public research institutes.^[21] As battery competition among East Asian countries continues to intensify, analyzing the dynamics of NCM battery research from an NIS perspective can provide useful insights for SandT policy makers.

Existing literature reviews of NCM battery research have been conducted by focusing on the technical content of individual applications and reviewing specific literature.^[22-24] Through a bibliometric analysis of data from the Web of Science (WoS), this research investigates publication trends, collaboration networks and the strategic positioning of countries in the NCM battery technology domain. Bibliometric analysis is useful for understanding accumulated scientific knowledge and dynamic change using large amounts of data and for reviewing large areas of research.^[25,26] By describing the major trends in NCM battery technology at national, organizational and individual levels, this analysis provides policy insights into NCM battery technology in East Asian countries. Furthermore, this study could guide the establishment of effective collaboration strategies for NCM batteries between East Asian countries, from a technology and policy perspective.

Based on the results of the literature review, we formulate the following research questions to achieve our research objectives.

RQ1: Who are the most influential contributors (national, organizational and individual) in NCM Battery research?

RQ2: What are the current research collaboration trends and status for NCM batteries in East Asian countries based on a NIS perspective?

METHODOLOGY

Data Collection

In this study, we used Clarivate's WoS database as the primary data source to analyze the research trends in NCM battery technology. WoS is one of the most authoritative academic databases globally, encompassing essential indices such as the Science Citation Index Expanded (SCIE), Social Science Citation Index (SSCI) and Emerging Sources Citation Index (ESCI).^[27] It should be noted that the numbers in the WoS database may vary depending on the timing of updates. To maintain consistency and accuracy, we established January 3, 2024, as the data reference date. The data search and download procedures were conducted on the same day to mitigate potential discrepancies or errors.

To identify papers on NCM battery technology, we refined the scope of our search to encompass secondary batteries, using keywords such as "batter*" and "recharge*." A conditional search expression was crafted to include specific terms like "ncm" or "Incmo," which refer to NCM batteries. Initially, the search yielded 1,560 articles. To focus exclusively on research papers, 83 cases in which the document type was not classified as article were excluded. Although NCM battery papers were first introduced to the WoS database in 2007, our analysis zeroed in on the last decade (2013-2022), a period marked by considerable growth in related research. Approximately 75% of all the papers, totaling 1,180 papers, were published within this timeframe. Further refinement involved the exclusion of papers in languages other than English, resulting in a final dataset of 1,164 papers for our analysis. The detailed query expression employed for the search was as follows: "TS=((("batter*") and ("secondary" or "recharge*" or "charg*" or "li" or "lithium") and ("ncm" or "Incmo")))." TS queries searched the title, abstract, author keywords and keywords using the topic search field used in WoS.

The retrieved data were extracted in the form of a plaintext file, encompassing all bibliographic and citation information. Descriptive statistical analysis was conducted using WoS and for collaboration and citation information analysis, VOSViewer 1.6.18 software was employed. In VOSViewer, the closer the distance between nodes, the more relevant they are and strong citation relationships are indicated by line thickness.^[28] Journal Citation Reports (JCR) served as a valuable resource for obtaining the Impact Factor (IF) and quartile information in the analysis. It should be noted that the base year for this comprehensive analysis was 2022.

RESULTS

Annual trends

Figure 1 illustrates the annual publication trends of NCM battery papers from 2013 to 2022. Notably, there has been a substantial surge in the number of NCM battery studies over the last decade, with a remarkable compound annual growth rate of 44.4%.

Aside from a slight dip in 2015, the annual trend demonstrates a consistent upward trajectory. From 2019 onward, in tandem with the expansion of related industries, there is a notable surge in the number of NCM battery papers, suggesting a sustained upward trajectory. After the annual number of papers exceeds 100, a sharp growth is evident in 2020, with a year-on-year increase of 62.2%. Papers published in the last three years comprise 66% (769) of the total number of papers analyzed, underscoring the rapid acceleration of NCM battery research.

National Analysis

Collaborations in NCM battery research span 42 countries, amounting to a total of 1,441 collaborations. Table 1 shows the top 10 countries for NCM battery research articles. Notably, the top three contributors by number of collaborations are China (651), Germany (204) and South Korea (202). The collective efforts of East Asian countries-including Japan and Taiwan-have resulted in approximately 64% of NCM battery papers being published over the last decade. It should be acknowledged that these numbers may have been counted twice in instances where multiple countries collaborated on a single study.^[29]

Figure 2 describes the overall trends in NCM battery research articles by graphs. Figure 3 illustrates the collaborative relationships between countries responsible for NCM battery research papers. For clarity, the visualization focuses on 17 countries that authored a minimum of five collaborative papers and demonstrated connections. Here, the node size corresponds to the number of papers, whereas the line thickness denotes the strength of the connection. The dominant contributors to NCM battery collaborations are China and Germany. In particular, China exhibits strong collaborative relationships with the United States, positioning itself at the forefront in global collaborative efforts. East Asian nations-including China, South Korea and Japan-are closely clustered or situated in close proximity, with

Taiwan being the exception. Taiwan's research cluster extends beyond geographical proximity and includes England and India.

Figure 4 further delves into the collaborative patterns illustrated in Figure 3, providing a year-wise breakdown. The color scheme signifies the average publication year, with shades closer to red indicating a more recent concentration of literature. Notably, the literature from East Asian countries-including China, South Korea and Taiwan-exhibits relatively recent concentrations.

In terms of citations, as shown in Figure 5, China (25,221), the United States (11,495) and Germany (10,595) secured the top three positions, followed by South Korea (7,304) and Japan (1,699). Notably, the citation count declines sharply beyond the fifth position. East Asian countries collectively contributed enormously to the total number of citations, accounting for 53% of them. Moreover, the United States has a high citation rate despite having a comparatively smaller number of papers, underscoring its established position as a technological powerhouse.

Figure 6 shows the citation relationships between countries, highlighting the close ties between China, South Korea, Germany and the United States, as well as the collaborative efforts between these nations.

Organizational Analysis

When considering the organization as the unit of analysis, collaborations on NCM battery research papers involved 955 organizations. Table 2 indicates the top 10 organizations for publishing NCM battery research articles, which are also described in graph format in Figure 7. The cumulative count of collaborative papers reached 2,680, with the three leading organizations in terms of the number of collaborative papers being the Chinese Academy of Sciences (CAS) (79), Central South University (68) and BASF SE (46). It is important to note potential instances of double counting, particularly when multiple organizations contribute to a single paper.

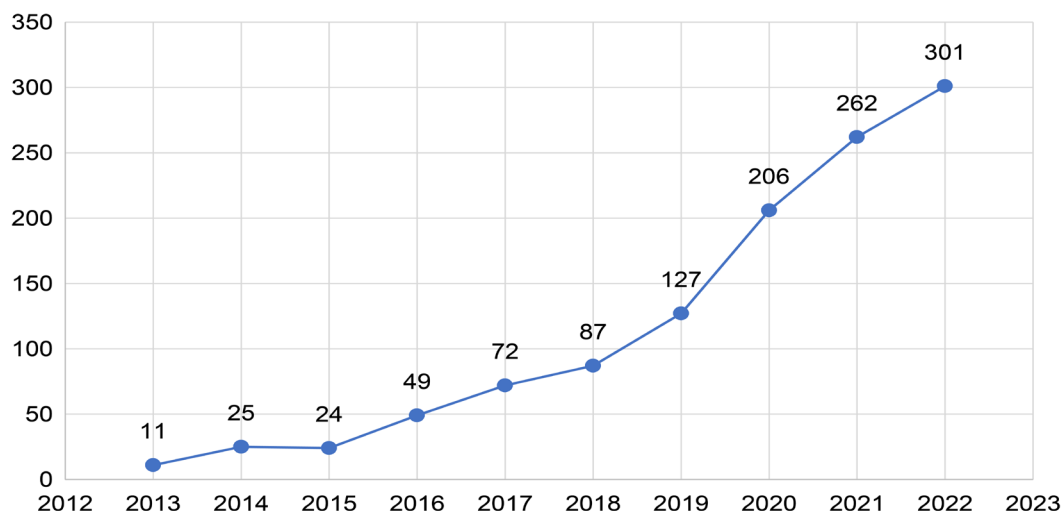


Figure 1: Annual trends of NCM battery research articles.

Table 1: Top 10 countries by NCM battery research articles.

Country	Documents	Citations
Peoples Republic of China	651	25,221
Germany	204	10,595
South Korea	202	7,304
USA	107	11,495
Japan	52	1,699
Israel	29	1,457
England	24	1,095
Taiwan	21	530
Switzerland	20	895
Australia	17	734

Figure 8 shows the collaborative relationships between organizations with respect to NCM battery papers. To facilitate efficient visualization, 122 organizations that authored at least five collaborative papers and exhibited connections are represented. The node size corresponds to the number of papers, whereas the line thickness reflects the connection strength.

Various clusters of collaborative relationships between organizations with respect to NCM battery papers are evident. The CAS-the most prolific collaborative organization-is positioned at the center of the network map, spearheading collaborations and forming a research cluster with institutions such as the Shanghai Institute of Technology and the University of Chinese Academy of Sciences. A similar pattern is evident for Central

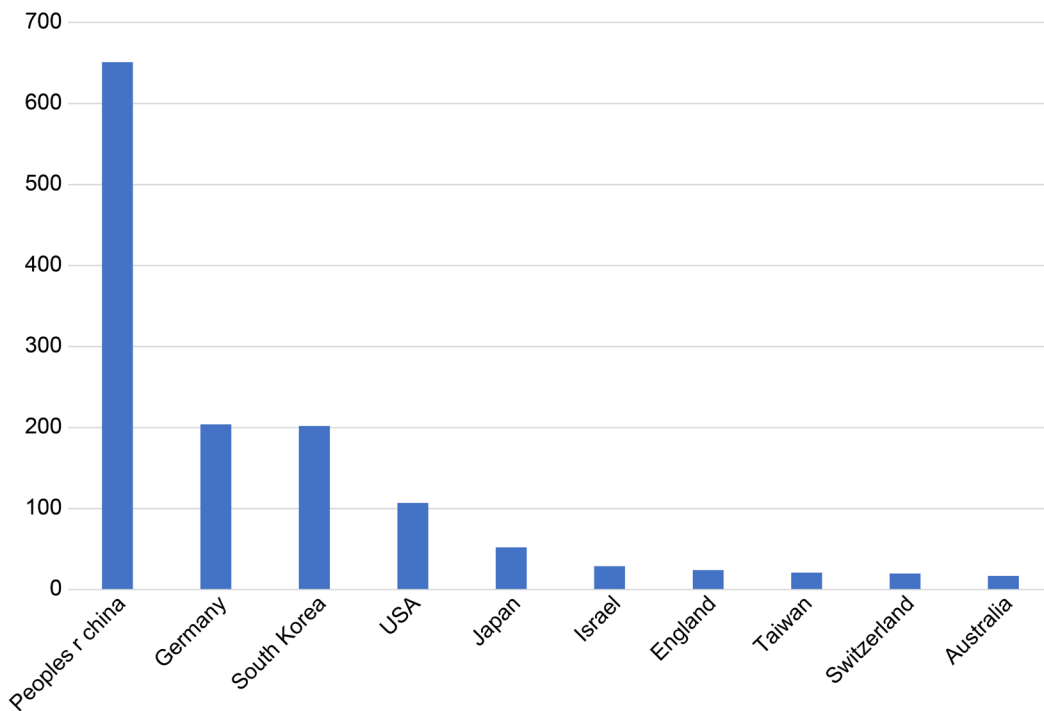


Figure 2: Trends in NCM battery research articles by country.

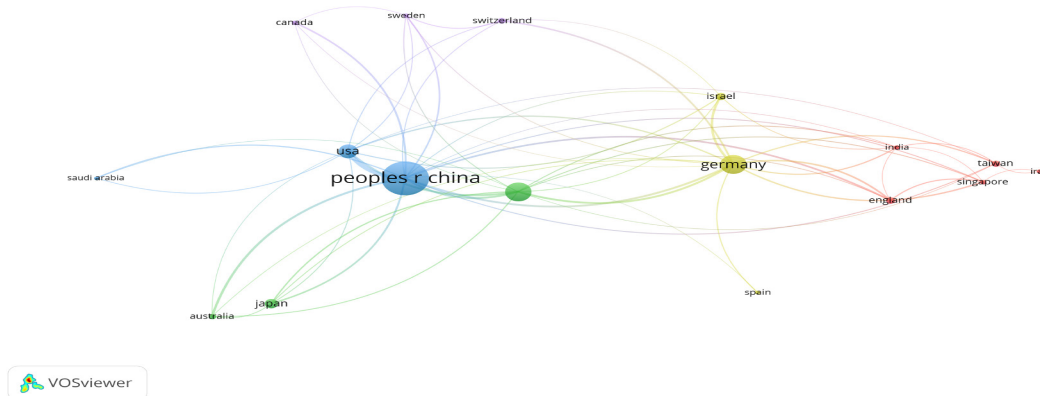


Figure 3: Collaboration network map of countries on NCM battery research articles.

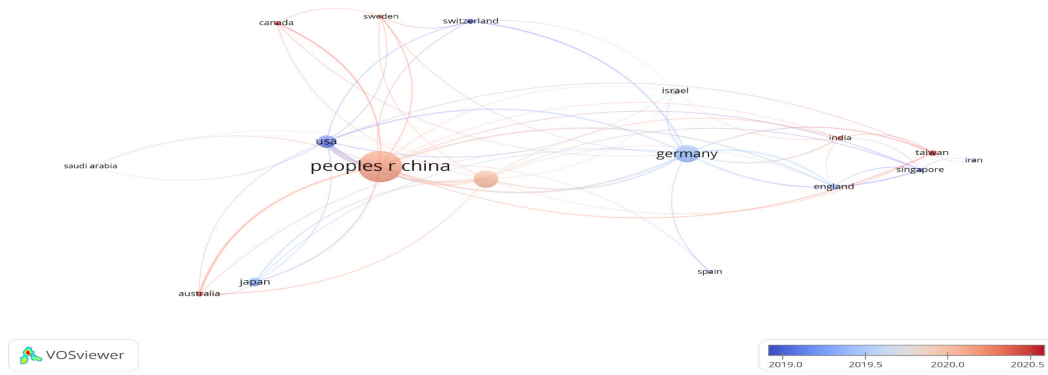


Figure 4: Collaboration network map of countries on NCM battery research articles by period.

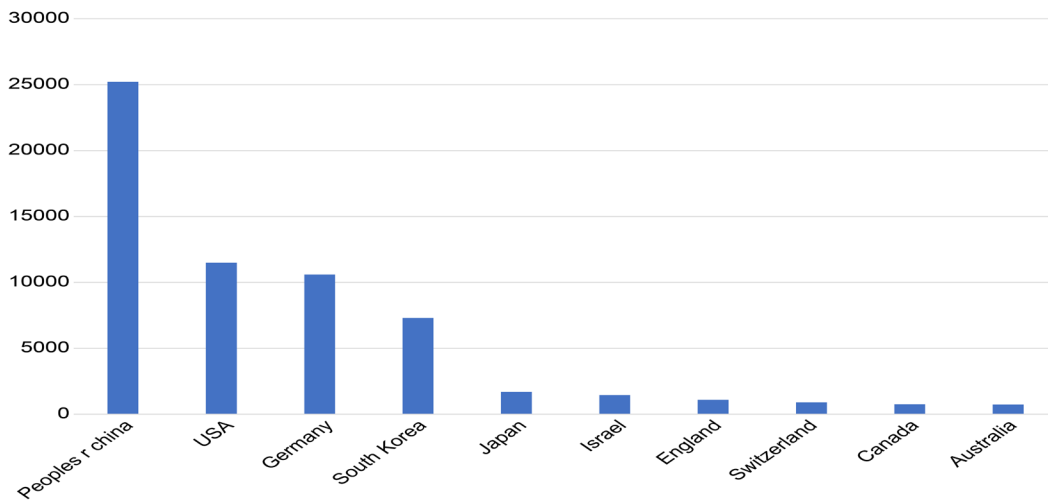


Figure 5: Trends in NCM battery research article citations by country.

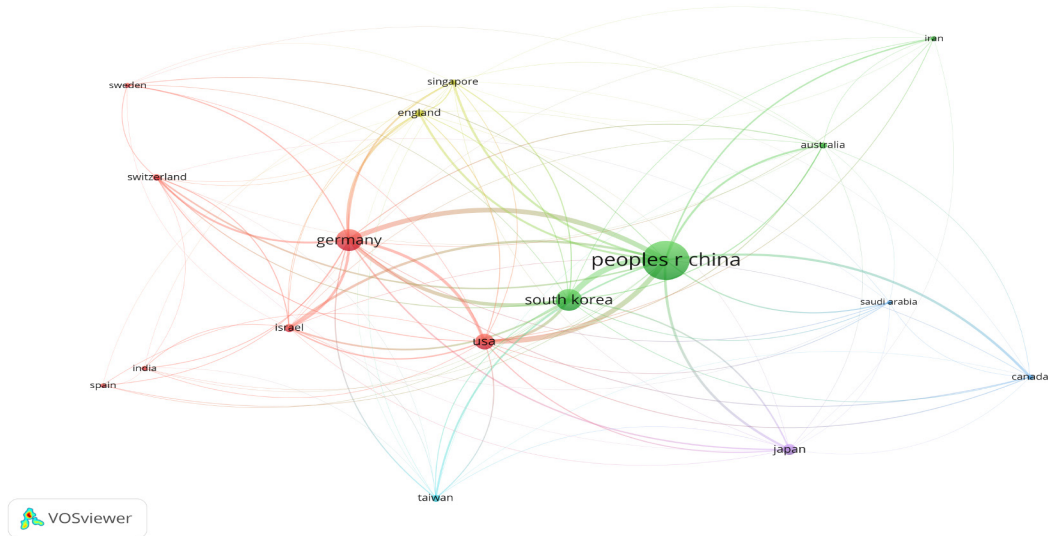


Figure 6: Citation network map of NCM battery research articles by country.

South University, which occupies a central position and forms a research cluster with institutions such as the Hunan University of Technology.

In general, Chinese Universities and Institutions dominate the collaborative landscape along with Germany's BASF and South

Korea's Hanyang University. BASF primarily collaborates with German institutions-such as the Helmholtz Institute Ulm-while Hanyang University engages in research clusters with South Korean institutions-such as the Korea University and Korea Institute of Science and Technology. Notably, inter-organizational

collaborations tend to be geographically proximate to home institutions.

Figure 9 illustrates cross-organizational collaboration over the years. The colors on the graph indicate the average publication year, with red representing more recent literature. Consistent with the country-level analysis, the visualization reveals a relatively recent concentration of NCM battery research papers from East Asian organizations, particularly from China and South Korea.

Table 2: Top 10 organizations publishing NCM battery research articles.

Organization	Documents	Citations
Chinese Academy of Sciences	79	2649
Central South University	68	7052
BASF SE	46	3594
Tsinghua University	45	2641
Justus Liebig University Giessen	40	3284
University of Münster	36	1933
University of Chinese Academy of Sciences	36	1217
Hanyang University	30	2706
Xiamen University	29	1316
Beijing Institute of Technology	28	1474

Figure 10 describes the trends in NCM battery research article citations by organization. Concerning citations, the Centre South University (7,052), Georgia Institute of Technology (4,806) and BASF SE (3,594) stand out, with East Asian institutions dominating this metric. Notably, Western institutions from the United States, Germany and other regions demonstrate high citation counts despite having a relatively smaller number of papers. Although a higher citation count is not an absolute indicator, it generally suggests higher quality papers.

Figure 11 shows the citation relationships between organizations. In contrast to collaborations, this visualization reveals interagency networks within the same country. Chinese institutions show close citation relationships in Clusters 1 (red) and 3 (blue), whereas Cluster 4 (yellow) represents the citation relationships of Western countries centered on Germany. South Korea exhibits a smaller number of citation relationships in Cluster 2 (green).

Researcher Analysis

Researcher-level analysis is crucial for strategically leveraging global collaborative research. This is driven by the fact that researchers possess distinct research domains and technical expertise, necessitating precise matching with demand for successful international collaborations. In the realm of NCM battery research, as shown in Table 3 and Figure 12 collaborations

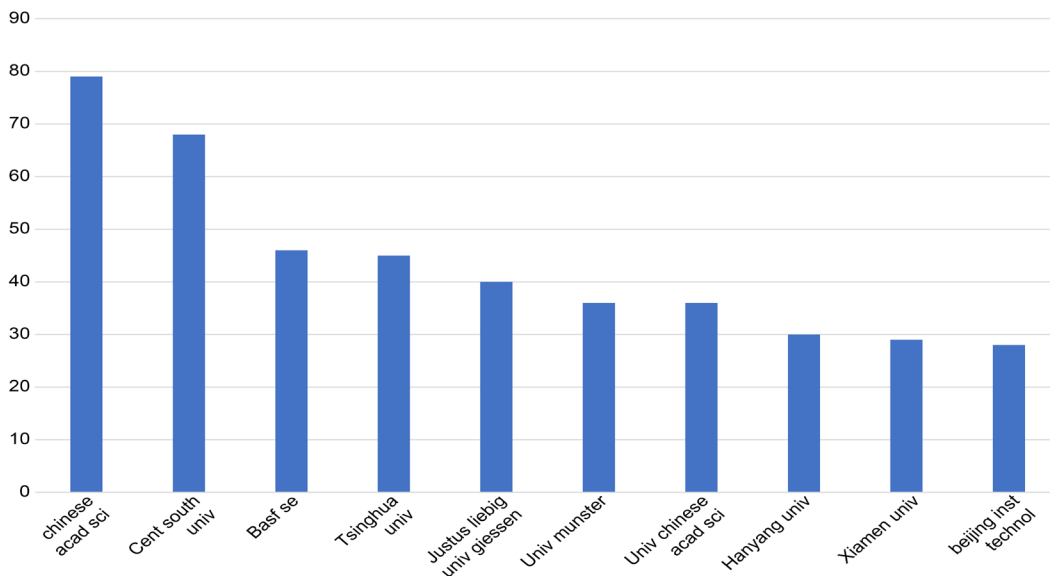


Figure 7: Trends in NCM battery research articles by organization.

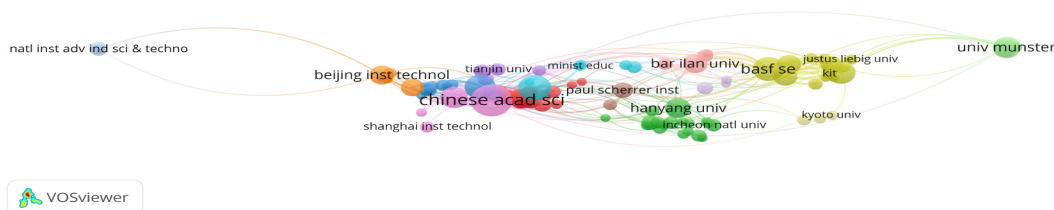


Figure 8: Organizational collaboration network map on NCM battery research articles

Figure 15 shows the network map for paper citations based on NCM battery research articles. The citation relationships among researchers with respect to NCM battery papers can be categorized into four main clusters. These relationships can

be efficiently visualized by focusing on researchers who have authored ten or more collaborative papers. Research Cluster 3 (blue), centered around Janek, Juergen, features the most collaborative papers. Cluster 4 (yellow) is centered around Winter, Martin, Cluster 2 (green) around Aurbach, Doron and finally Cluster 1 (red) around Sun, Yang-Kook. Clusters 3 and 4 consist of German researchers predominantly. Cluster 2 is centered around the Israeli researcher Aurbach, Doron while Cluster 1 is focused on South Korean researchers Sun, Yang-Kook. Despite China's dominance in the top positions in the country-, organization- and researcher-level analyses, it is not prominent in the top positions of this researcher-level citation relationship analysis. This could be attributed to our methodology, which only included key researchers with more than ten papers, potentially excluding emerging East Asian researchers who may not meet this publication threshold.

Table 3: Top 10 researchers on NCM battery research articles.

Author	Documents	Citations
Janek, Juergen	39	3414
Winter, Martin	28	1270
Brezesinski, Torsten	27	2217
Aurbach, Doron	24	1388
Gasteiger, Hubert A.	24	1265
Hartmann, Pascal	19	2570
Sun, Yang-Kook	18	2193
Markovsky, Boris	16	1216
Novak, Petr	13	525
Wang, Qingsong	13	585

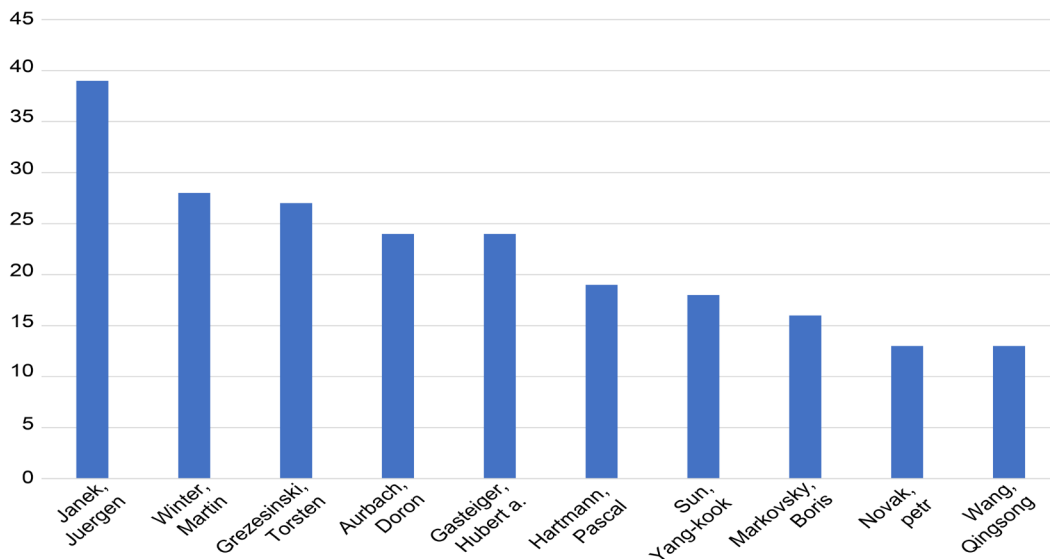


Figure 12: Trends in NCM battery research articles by researcher.

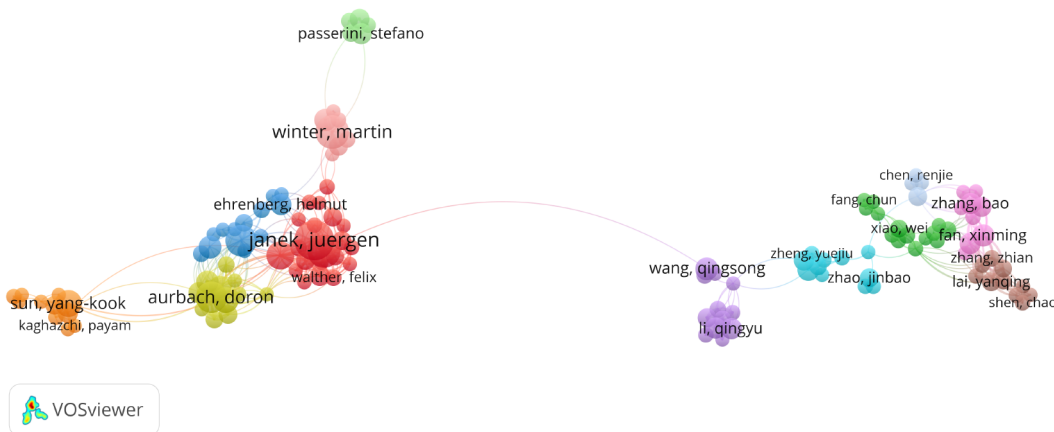


Figure 13: Collaboration network map of researchers on NCM battery research articles.

Journal and Document Analysis

In our previous analysis, we identified the country, organization and researcher characteristics of NCM battery research papers. Thus, a key question arises: what are the most prominent journals and articles in this field? Over the past ten years, 229 journals

have published papers on NCM battery technology. As described in Table 4, The journal with the highest number of published articles is the Journal of the Electrochemical Society with 80 papers, followed by the Journal of Power Sources with 78 papers and ACS Applied Materials and Interfaces with 63 papers. Most of these journals are ranked Q2 or higher. However, the Journal

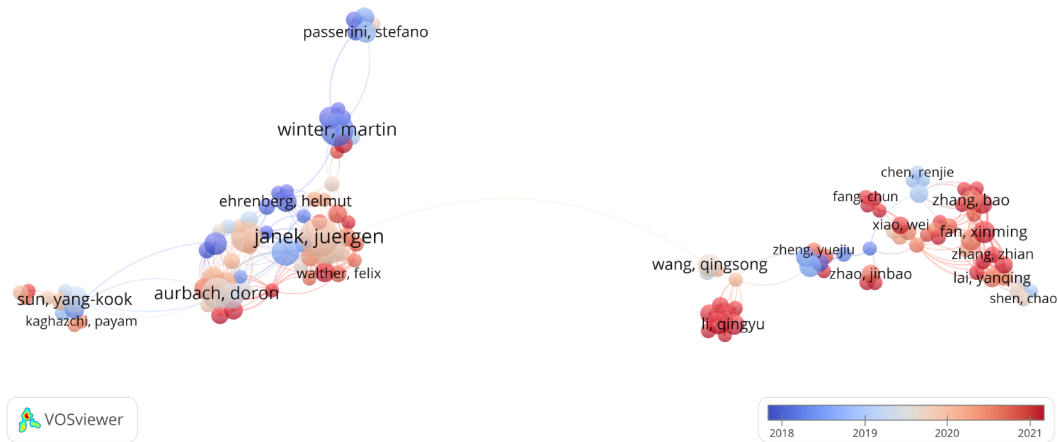


Figure 14: Collaboration network map of researchers on NCM battery articles by period.

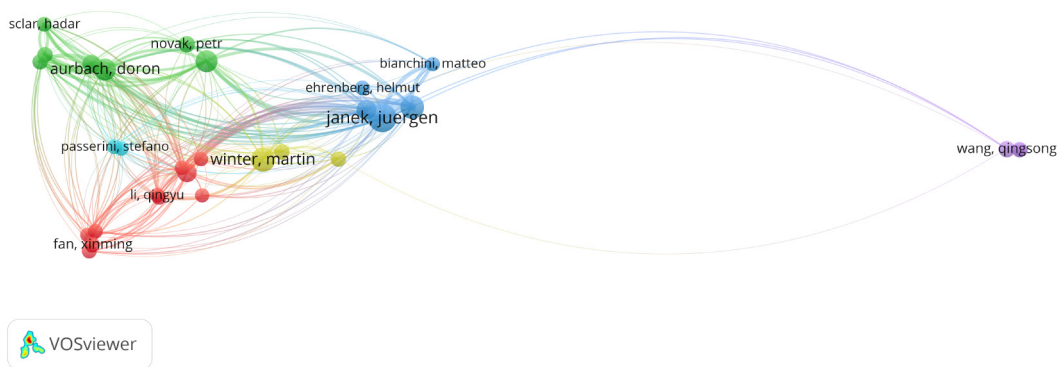


Figure 15: Researcher citation network map on NCM battery research articles.

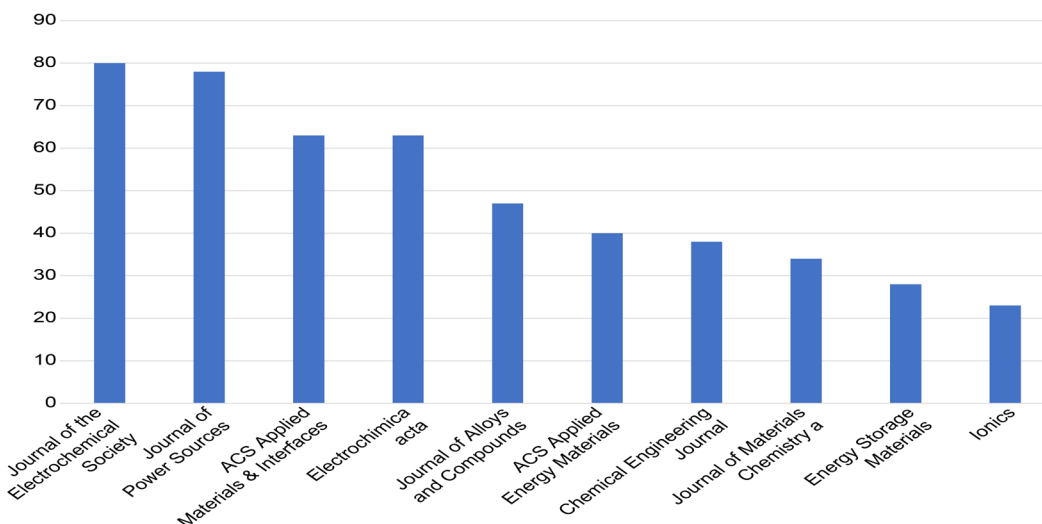
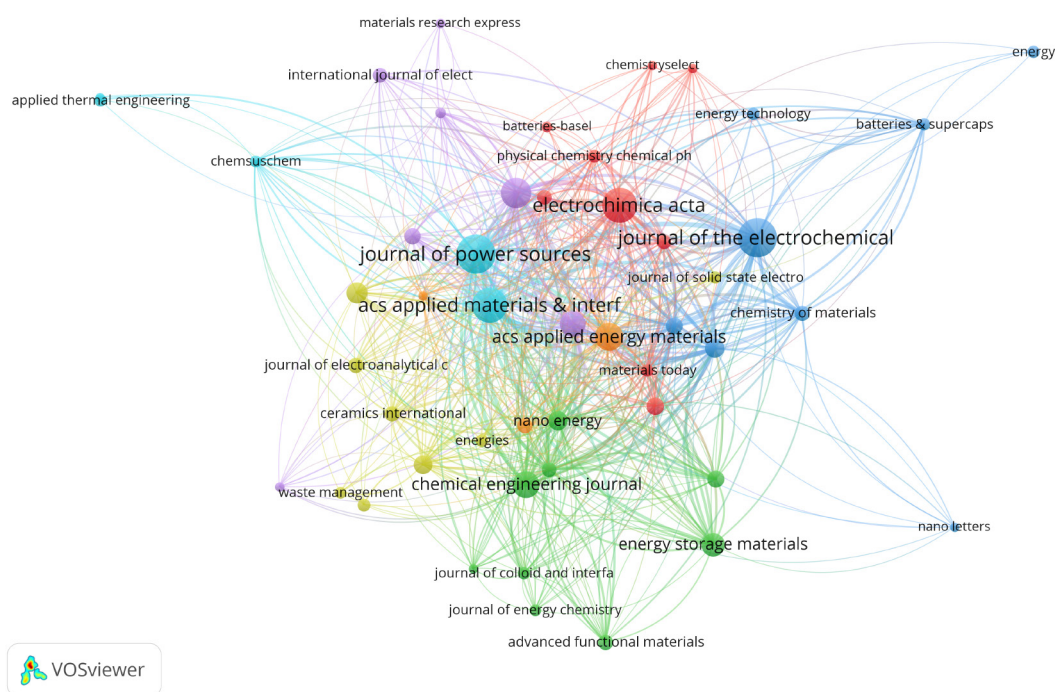


Figure 16: Citation trends in NCM battery research articles by journal

Table 4: Top 10 journals by NCM battery research articles.

Source	Documents	Citations	IF	Quartile
Journal of the Electrochemical Society	80	2,188	3.9	Q3
Journal of Power Sources	78	4,897	9.2	Q1
ACS Applied Materials and Interfaces	63	2,913	9.5	Q1
Electrochimica ACTA	63	2,159	6.6	Q2
Journal of Alloys and Compounds	47	1,016	6.2	Q2
ACS Applied Energy Materials	40	799	6.4	Q2
Chemical Engineering Journal	38	808	6.4	Q2
Journal of Materials Chemistry A	34	1,891	11.9	Q1
Energy Storage Materials	28	1378	20.4	Q1
Ionics	23	160	2.8	Q3

**Figure 17:** Journal citation network map on NCM battery research articles.

of the Electrochemical Society is an exception, being ranked Q3. Figure 16 illustrates the citation trends of NCM battery research articles with graphs.

Although Materials Today has published only eight articles, it leads in both the total number of citations and the highest average number of citations per article, which could be attributed to the publication of review articles. However, further analysis is required to confirm this hypothesis. In terms of the number of articles published, the Journal of Power Sources and ACS Applied Materials and Interfaces are notable, along with others that have similar rankings. Considering the average number of citations, Materials Today, ACS Energy Letters and Advanced Energy Materials, among others, rank highly.

Figure 17 demonstrates the citation relationships between journals. For this visualization, journals that published five or more NCM battery research articles were selected, resulting in 49 journals with notable citation relationships.

Figure 18 illustrates the dynamic citation relationships between these journals, which can be segmented by year to identify emerging journals in the field. These insights could be valuable for NCM battery researchers when selecting appropriate journals for their submissions.

We conducted a paper-by-paper citation analysis to identify the key NCM battery research papers. In total, 1,164 papers were cited 44,229 times during the study period. Table 5 presents the top ten most-cited papers. The most-cited paper-authored by Nitta^[30] and published in 2015-discusses the major technologies

Table 5: Top 10 articles by NCM battery research citations.

Title	Authors	Publication Year	Citations
Li-ion battery materials: present and future.	Nitta, N. <i>et al.</i>	2015	4,686
Understanding the degradation mechanisms of $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2$ cathode material in lithium-ion batteries.	Jung, S. K. <i>et al.</i>	2014	825
Capacity fade in solid-state batteries: interphase formation and chemomechanical processes in nickel-rich layered oxide cathodes and lithium thiophosphate solid electrolytes.	Koerver, R. <i>et al.</i>	2017	591
Thermal runaway features of large format prismatic lithium-ion battery using extended volume accelerating rate calorimetry.	Feng, X. <i>et al.</i>	2014	498
Significantly improving cycling performance of cathodes in lithium-ion batteries: The effect of Al_2O_3 and LiAlO_2 coatings on $\text{LiNi}_{0.6}\text{Co}_{0.2}\text{Mn}_{0.2}\text{O}_2$.	Liu, W. <i>et al.</i>	2018	485
Implantable solid electrolyte interphase in lithium-metal batteries.	Cheng, X. B. <i>et al.</i>	2017	447
Anisotropic lattice strain and mechanical degradation of high- and low-nickel NCM cathode materials for Li-ion batteries.	Kondrakov, A. O. <i>et al.</i>	2017	432
Problems and their origins of Ni-rich layered oxide cathode materials.	Zhang, S. S.	2020	367
Crack-free single-crystalline Ni-rich layered NCM cathode enable superior cycling performance of lithium-ion batteries.	Fan, X. <i>et al.</i>	2020	329
A promising approach for the recovery of high value-added metals from spent lithium-ion batteries.	Hu, J. <i>et al.</i>	2017	326

DISCUSSION

Over the past decade, research on NCM batteries has increased rapidly, with an average annual growth rate of 44.4%. This surge aligns with evolving industry trends—such as the move toward electrification and wireless technologies—suggesting that the growth trend is likely to continue. Over the last three years, there has been a particularly notable upswing in the number of NCM battery research papers originating from East Asian institutions, particularly from China and South Korea. Nevertheless, German researchers remain key contributors and influencers in the field. The value of this study lies in the scientific and quantitative analysis of NCM battery research trends, a vital area in secondary battery technology that is attracting increasing attention. Our findings are expected to provide insights for NIS designers and SandT policy researchers in East Asia.

Our research suggests that East Asia—particularly China—is poised to continue its leadership in NCM battery research and has accelerated its efforts in recent years. In line with the science and technology policies in East Asia of utilizing public research institutions, CAS is leading China's NCM battery research. Another East Asian country, South Korea, is also expanding its

research influence, led by Hanyang University. While traditional technological leaders such as the United States and Germany maintain a considerable presence in this domain, their recent focus has shifted toward next-generation all-solid-state and lithium-sulfur batteries. Nevertheless, traditional technology leaders still have a strong influence at the level of individual researchers (Janek, J, Winter, M etc.). From the NIS perspective, NCM batteries may emerge as a strategic niche in East Asian countries. This is exemplified by the substantial efforts China and South Korea have allocated to NCM battery technology research. The development of effective innovation systems encompasses various elements such as innovation activities, funding, institutions, policies, regulations, cultural factors, human resources and scientific achievements.^[32] In the sphere of NCM batteries, East Asian countries have robust institutions, human resources, active innovation and tangible scientific outcomes. However, in East Asia, the collaborative engagement of companies and research institutions in NCM battery research remains limited. The synergy known as the university-industry-government triad is crucial for the success of any innovation system.^[33] In Europe and the United States, this collaboration is particularly strong with global companies such as BASF leading

research initiatives. To enhance their innovation systems, East Asian countries need to focus on strengthening their collaborative ties. In particular, we found a lack of cooperation between East Asian countries despite their geographical proximity; a follow-up study should conduct a detailed technology-specific in-depth literature review to uncover this.

Despite the valuable bibliometric contributions of our study to the understanding of East Asian NIS, it is important to recognize its inherent limitations. First, our analysis was confined to data from the WoS Core Collection. Many bibliometric studies have also used data from other databases-such as the SCOPUS and Dimensions databases. Although there is no definitive method for determining which database is superior, it is crucial to acknowledge that different database selections may yield varying results. This should be carefully considered when interpreting the findings of such analyses. Despite these limitations, we believe that our analysis offers considerable insights into the strengths and national and organizational characteristics of East Asia in NCM battery technology research, providing valuable information for SandT policymakers and researchers in the field.

Future research could benefit from segmentation analyses based on specific applications. Although our study provides an overview of the macro landscape of NCM battery technology research, it is important to note that NCM batteries are used in a diverse range of applications, from automobiles to power systems and consumer electronics. From a technology planning perspective, a more granular analysis focusing on these specific applications is expected to yield more insightful results. Furthermore, separate comparisons of citation and research networks by country may reveal new patterns that should be addressed in future studies of this kind.

CONCLUSION

NCM batteries represent a high-tech sector in which East Asia has the potential to lead research, in contrast to most high-tech fields in which Western countries-particularly the United States and Europe-typically dominate. We identified the presence of potential and dynamism of East Asia in NCM battery research. Our findings offer valuable guidance to East Asian SandT policymakers and NCM battery researchers. Thus, a critical question emerges: what technological strategy should be adopted? Policymakers should thoroughly analyze their country's status and resources to establish a strategic direction. Options include maintaining leadership in NCM batteries or leveraging their strengths to develop pioneering alternatives, such as LFP batteries. Building an East Asian alliance on NCM batteries could overcome the technological challenges by Western countries. If building alliances in NCM battery technology research is the goal, the insights into influential countries, organizations and researchers provided by this study could be persuasive. Additionally, NCM

battery researchers should develop a robust patent strategy to safeguard their research and establish a strategic position to accelerate the development of next-generation batteries.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ABBREVIATIONS

EV: Electric Vehicle; **LIBs:** Lithium-Ion Batteries; **NCM:** Nickel Cobalt Manganese oxide; **NCA:** Nickel Cobalt Aluminum oxide; **LFP:** Lithium iron Phosphate; **NIS:** National Innovation Systems; **SandT:** Science and Technology; **WoS:** Web of Science; **SCIE:** Science Citation Index Expanded; **SSCI:** Social Science Citation Index; **ESCI:** Emerging Sources Citation Index; **JCR:** Journal Citation Reports; **IF:** Impact Factor; **CAS:** Chinese Academy of Sciences.

REFERENCES

1. Forsythe CR, Gillingham KT, Michalek JJ, Whitefoot KS. Technology advancement is driving electric vehicle adoption. *Proceedings of the National Academy of Sciences.* 2023;120(23):e2219396120.
2. Choi YHC, H.S. Technology Trends for Lithium Secondary Batteries. *ETRI Journal.* 2023;38(5):90-9.
3. Fleischmann J, Hanicke M, Horetsky E, Ibrahim D, Jautelat S, et al. Battery 2030: Resilient, sustainable and circular. *McKinsey and Company.* 2023:2-18.
4. Cunanan C, Tran M-K, Lee Y, Kwok S, Leung V, et al. A review of heavy-duty vehicle powertrain technologies: Diesel engine vehicles, battery electric vehicles and hydrogen fuel cell electric vehicles. *Clean Technologies.* 2021;3(2):474-89.
5. Panchal S, Gudlanarva K, Tran M-K, Fraser R, Fowler M. High reynold's number turbulent model for micro-channel cold plate using reverse engineering approach for water-cooled battery in electric vehicles. *Energies.* 2020;13(7):1638.
6. Tran M-K, Akinsanya M, Panchal S, Fraser R, Fowler M. Design of a hybrid electric vehicle powertrain for performance optimization considering various powertrain components and configurations. *Vehicles.* 2020;3(1):20-32.
7. Xu C, Dai Q, Gaines L, Hu M, Tukker A, et al. Future material demand for automotive lithium-based batteries. *Communications Materials.* 2020;1(1):99.
8. Quan J, Zhao S, Song D, Wang T, He W, et al. Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies. *Science of The Total Environment.* 2022;819:153105.
9. Bridge G, Faigen E. Towards the lithium-ion battery production network: Thinking beyond mineral supply chains. *Energy Research and Social Science.* 2022;89:102659.
10. Dang R, Qu Y, Ma Z, Yu L, Duan L, et al. The effect of elemental doping on nickel-rich NCM cathode materials of lithium ion batteries. *The Journal of Physical Chemistry C.* 2021;126(1):151-9.
11. IEA. *Global EV Outlook 2023.* International Energy Agency; 2023.
12. Feng X, Ren D, Ouyang M. Safety of lithium battery materials chemistry. *Journal of Materials Chemistry A.* 2023;11(46):25236-46.
13. Lee JS, Kim SK. Techno-economic Analysis on the Present and Future of Secondary Battery Market for Electric Vehicles and ESS. *Journal of Information Technology Applications and Management.* 2023;30(1):1-9.
14. Dongmei S, Jing W. Analysis of battery technology and industry development strategy and trend in China, Japan and South Korea. *Energy Storage Science and Technology.* 2023;12(2):615.
15. Chen Q, Lai X, Hou Y, Gu H, Lu L, et al. Investigating the environmental impacts of different direct material recycling and battery remanufacturing technologies on two types of retired lithium-ion batteries from electric vehicles in China. *Separation and Purification Technology.* 2023;308:122966.
16. Sebastien M. Strengthening clean energy supply chains for decarbonisation and economic security. 2023.
17. Lee SY. A Study on the Policies and Recent Development of Electric Vehicle Battery Industry. *The Comparative Economic Review.* 2021;28(1):71-103.
18. Liu X, Wu Z, Xie L, Sheng L, Liu J, et al. Prelithiation Enhances Cycling Life of Lithium-Ion Batteries: A Mini Review. *Energy and Environmental Materials.* 2023:e12501.
19. S.Korea to inject \$15 bn in rechargeable battery sector by 2030 [press release]. *The Korea Economic Daily* 2023.
20. Yang C, Mu X-Y. Mapping the trends and prospects of battery cathode materials based on patent landscape. *Frontiers in Energy.* 2023:1-11.

21. Krishna VV. Universities in the national innovation systems: Emerging innovation landscapes in Asia-Pacific. *Journal of Open Innovation: Technology, Market and Complexity*. 2019;5(3):43.
22. Jung CH, Shim H, Eum D, Hong SH. Challenges and recent progress in LiNi_xCo_yMn_{1-x-y}O₂ (NCM) cathodes for lithium ion batteries. *Journal of the Korean Ceramic Society*. 2021;58(1):1-27.
23. Chakraborty A, Kunnikuruvaan S, Dixit M, Major DT. Review of computational studies of NCM cathode materials for Li-ion batteries. *Israel Journal of Chemistry*. 2020;60(8-9):850-62.
24. Chakraborty A, Kunnikuruvaan S, Kumar S, Markovsky B, Aurbach D, et al. Layered cathode materials for lithium-ion batteries: review of computational studies on LiNi_{1-x-y}Co_xMn_yO₂ and LiNi_{1-x-y}Co_xAl_yO₂. *Chemistry of Materials*. 2020;32(3):915-52.
25. Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*. 2021;133:285-96.
26. Lim WM, Kumar S. Guidelines for interpreting the results of bibliometric analysis: A sensemaking approach. *Global Business and Organizational Excellence*. 2024;43(2):17-26.
27. Li K, Rollins J, Yan E. Web of Science use in published research and review papers 1997-2017: A selective, dynamic, cross-domain, content-based analysis. *Scientometrics*. 2018;115(1):1-20.
28. Van Eck NJ, Waltman L. Citation-based clustering of publications using CitNetExplorer and VOSviewer. *Scientometrics*. 2017;111:1053-70.
29. Liu J, Li J, Wang J. In-depth analysis on thermal hazards related research trends about lithium-ion batteries: A bibliometric study. *Journal of Energy Storage*. 2021;35:102253.
30. Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: present and future. *Materials today*. 2015;18(5):252-64.
31. Lund B, Shamsi A, Ghamgosar A, Raju NV, Dehdarirad H, et al. Independent Researchers: A Bibliometric Analysis. *Journal of Scientometric Research*. 2023;12(2):275-84.
32. Putera PB, Suryanto S, Ningrum S, Widianingsih I, Rianto Y. Three decades of discourse on science, technology and innovation in national innovation system: A Bibliometric Analysis (1990-2020). *Cogent Social Sciences*. 2022;8(1):2109854.
33. Yaghmaie P, Vanhaverbeke W. Identifying and describing constituents of innovation ecosystems: A systematic review of the literature. *EuroMed Journal of Business*. 2020;15(3):283-314.

Cite this article: Yoon HY, Lee J, Choe H. Analyzing Research Collaboration Trends in NCM Batteries Using Bibliometric Analysis. *J Scientometric Res*. 2024;13(3s):s39-s52.