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Research Article

Multifunctional Polymer Composite Materials for Thermal-Structural-Electrical Integration in Electric Vehicle Batteries: A Bibliometric and Science Mapping Review (1995-2025)

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ABSTRACT

The rapid advancement of Electric Vehicle (EV) technologies has intensified the demand for multifunctional adhesive-based polymer composites capable of simultaneously addressing structural integrity, thermal management, and electrochemical stability. This study presents a comprehensive bibliometric analysis of 377 publications (1995-2025) retrieved from the Scopus database to systematically evaluate global research trends, influential contributors, and thematic evolution in this domain. The results indicate a significant growth trajectory with an average annual growth rate of 14.56%, highlighting the increasing scientific and industrial relevance of the field. Performance analysis reveals a highly concentrated publication structure, where leading journals contribute over 22% of total output, and dominant countries account for a major share of research productivity. Collaboration analysis demonstrates a moderately dense global network, characterized by hub-centric structures and regional clustering. The conceptual-thematic framework identifies three major research domains: electrochemical systems, polymer-adhesion science, and advanced battery technologies, with polymer-based materials acting as a critical integrative component. Keyword co-occurrence analysis, comprising 314 keywords, 13,210 links, and a total link strength of 28,446, confirms a highly interconnected and multidisciplinary research landscape. The findings highlight a clear transition from fundamental electrochemical studies toward application-driven material innovation, emphasizing interface engineering and multifunctional performance optimization. This study provides a structured and quantitative understanding of the evolving research landscape, offering strategic insights for the development of next-generation adhesive-based polymer systems for high-performance EV battery applications.

Keywords: Adhesives, Electric Vehicles, Interface Engineering, Lithium-ion Batteries, Polymer Composites.

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INTRODUCTION

The rapid transition toward electric mobility has intensified the need for advanced material systems that can simultaneously address the structural, thermal, and safety requirements of EV battery packs, where lithium-ion batteries act as the core energy storage units governing performance and reliability (Murugan *et al.*, 2025). In this context, adhesive-based polymer matrix composites have emerged as critical enablers, replacing conventional fastening techniques by offering uniform stress distribution, lightweight design, and compatibility with dissimilar materials (Karthikeyan and Naveen, 2025). However, the growing complexity of EV battery architectures (Khan and Cameron, 2025) has introduced multifunctional demands on adhesive systems, requiring them to deliver not only strong bonding but also efficient thermal management, mechanical durability, and electrochemical stability under cyclic loading and harsh operating conditions (Zheng *et al.*, 2023). Despite significant advancements through the incorporation of thermally conductive fillers and hybrid composite strategies (Hemath *et al.*, 2020), a persistent trade-off between thermal conductivity and mechanical integrity remains inadequately resolved (Zhang *et al.*, 2026) and existing research is highly fragmented across disciplines such as materials science (dell'Isola *et al.*, 2016), electrochemistry (Glasstone, 2011), and mechanical engineering (Etukudoh *et al.*, 2024). Furthermore, current literature lacks a unified quantitative synthesis that systematically captures the evolution, thematic structure, and emerging directions of

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multifunctional adhesive systems specifically tailored for EV battery applications. Therefore, the primary objective of this study is to perform a comprehensive bibliometric analysis to (i) quantify global research trends, (ii) identify influential contributors and collaboration networks, and (iii) map the conceptual and thematic evolution of adhesive-based polymer composites in EV battery systems. It is hypothesized that the research field has undergone a rapid transition toward multifunctional material design, with increasing emphasis on integrating thermal, mechanical, and electrochemical performance within a single material system. Unlike previous review articles, which primarily focus on material design, electrochemical performance, thermal management, or adhesive technologies individually, this study provides a comprehensive bibliometric and science-mapping analysis that quantitatively evaluates the evolution of research on multifunctional polymer composites, lithium-ion batteries, and adhesive materials for electric vehicle battery applications. By integrating performance analysis, collaboration networks, conceptual structure, and thematic evolution, this review reveals emerging research trends, influential contributors, research gaps, and future directions that are not systematically synthesized in conventional narrative reviews. Therefore, the present work offers a unique quantitative perspective on the development of this interdisciplinary research field as shown illustrated in Figure 1.

METHODOLOGY

The methodology adopted in this study is based on a systematic and reproducible bibliometric framework designed to quantitatively evaluate the research landscape of adhesive-based polymer matrix composites for EV battery applications (Zhang *et al.*, 2025). Bibliographic data were exclusively retrieved from the Scopus database because it is one of the largest and most comprehensive multidisciplinary citation databases, offering broad coverage of peer-reviewed journals in materials science, engineering, energy, and polymer research (Khudzari *et al.*, 2018). Scopus was selected due to its extensive indexing, standardized bibliographic metadata, citation information, and compatibility with bibliometric tools such as Bibliometrix and VOSviewer, which facilitate reliable science mapping and network analysis (Baas *et al.*, 2020). The use of a single, consistently indexed database also minimizes duplication and metadata inconsistencies that may arise when combining records from multiple databases (Christen, 2011; Ullah *et al.*, 2023). A structured search strategy was developed using the TITLE-ABS-KEY (Title, Abstract, and Keywords) field to ensure thematic relevance, incorporating key terms related to adhesives, polymers/composites, and battery or EV systems. The final search query was formulated as: (TITLE-ABS-KEY (adhesive) AND TITLE-ABS-KEY (polymer* OR composite*) AND TITLE-ABS-KEY (battery* OR "electric vehicle*" OR ev)) refer to Supplementary Material S1. The search was refined by applying strict inclusion criteria, including publication years from 1995 to 2025, document type restricted to research articles, English language, and relevant subject areas such as materials science, chemical engineering, and energy systems. This process yielded an initial dataset, which was further screened to remove duplicates, incomplete records, and non-relevant studies, resulting in a final dataset suitable for analysis. The Scopus search and data export were conducted in [January 2026]; accordingly, all journal impact factor values, citation counts, and related performance metrics reported in this study reflect the data available as of that retrieval date and may not capture subsequent updates.

The extracted bibliographic records were exported in Comma-Separated Values (CSV) format, containing comprehensive metadata including authors, titles, abstracts, keywords, affiliations, and citation information (Turki *et al.*, 2021). Data preprocessing involved cleaning and standardization of keywords to minimize redundancy caused by variations in terminology, abbreviations, and plural forms (Gharatkar *et al.*, 2017). This step ensured consistency and improved the accuracy of subsequent network analyses (Donegan *et al.*, 2013). The processed dataset was analyzed using the Bibliometrix package implemented in the R statistical computing environment (version 4.3.1), which provides a comprehensive framework for bibliometric and scientometric analysis (Marlés-Sáenz *et al.*, 2025). The Biblioshiny interface was utilized to facilitate interactive visualization, data exploration, and validation of results (Thakuria *et al.*, 2023). The complete analytical workflow and corresponding R scripts are provided in Supplementary Material S1 for reproducibility and transparency.

Both performance analysis and science mapping techniques were employed to comprehensively assess the research domain (Gan *et al.*, 2022). Performance indicators included annual scientific production, most productive authors, influential journals, country-level contributions, and citation metrics, which collectively reflect the growth and impact of the field (Ovezmyradov, 2023). Science mapping techniques such as keyword co-occurrence analysis, co-citation analysis, and thematic mapping were applied to identify major research clusters, intellectual structures, and emerging themes (Chen *et al.*, 2023; Wei *et al.*, 2019). Network visualization tools, including VOSviewer, were utilized to generate collaboration and keyword networks, enabling the interpretation of relationships among authors, institutions, and research topics (Bukar *et al.*, 2023). This integrated methodological framework ensures a robust, transparent, and reproducible analysis of the evolving research landscape in multifunctional adhesive systems for EV battery technologies as depicted in Figure 2.

RESULTS

Unless otherwise stated, all citation counts and bibliometric indicators reported in this section correspond to the Scopus database as accessed on [15-01-2026].

Annual Scientific Production

The annual scientific production in the field of multifunctional adhesive-based polymer matrix composites for EV battery applications (1995-2025) reflects a clear transition from a nascent research area to a rapidly expanding and strategically important domain (Yao *et al.*, 2023). A total of 377 publications were analysed, exhibiting a strong average annual growth rate of 14.56%, which underscores sustained scientific and industrial interest (Mostaghis *et al.*, 2025). During the early phase (1995-2003), research activity remained limited, with only 1-2 publications per year, accounting for less than 1% of annual output, and primarily focused on fundamental studies in adhesion science and polymer chemistry (Barbosa *et al.*, 2022). This indicates a foundational stage with minimal application-oriented research. The subsequent growth phase (2005-2014) showed a steady increase in output from 4 publications in 2005 to 9 in 2014 (≈125% growth), marking the transition toward applied research in composite materials and early battery system integration.

A notable feature of this phase is the exceptionally high citation impact observed between 2005 and 2010, particularly in 2007 (42.74 citations per article) and 2011 (141.40 citations per article). This elevated citation intensity can be attributed to the emergence of foundational and highly cited works in polymer binders, electrode interface engineering, and nanocomposite materials (Cholewinski *et al.*, 2021). These studies coincided with the rapid advancement of lithium-ion battery technology, where critical challenges such as electrode stability, adhesion, and interfacial degradation were first systematically addressed (Adebanjo *et al.*, 2025). As a result, these early contributions became benchmark references, widely cited across subsequent research in energy storage, materials science, and EV battery development (Trahey *et al.*, 2020). From 2015 onwards, the field entered an exponential growth phase, with publications increasing from 14 in 2016 to 30 in 2020, and further to 57 in 2024 and 59 in 2025, contributing nearly 15% of total publications in the final two years (Trahey *et al.*, 2020). This surge is strongly linked to the global expansion of EV technologies and the increasing demand for multifunctional materials capable of integrating thermal management, mechanical integrity, and electrochemical stability (Boretti, 2025). The average citations per document declined in recent years (11.65 in 2024; 3.14 in 2025); this trend is primarily due to shorter citation windows rather than diminished research quality. The results confirm a high-growth, high-impact research trajectory driven by both technological demand and foundational scientific advancements as illustrated in Figure 3.

The observed exponential growth trend is consistent with previous bibliometric analyses of EV batteries and advanced energy materials, which also reported a rapid increase in publications after 2015 due to accelerated electrification, government funding, and industrial investment. Compared with earlier bibliometric

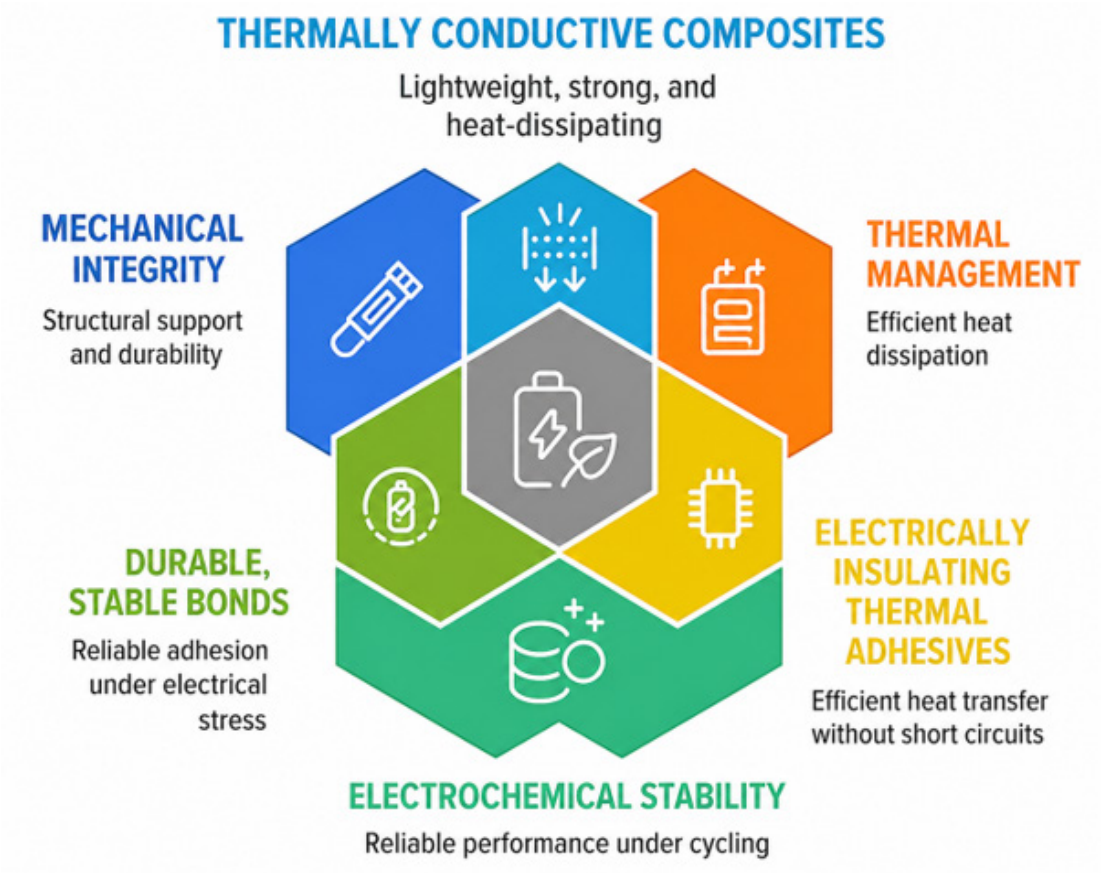


Figure 1: Key Functional Attributes of Thermally Conductive Polymer Composite Adhesives for EV Batteries.

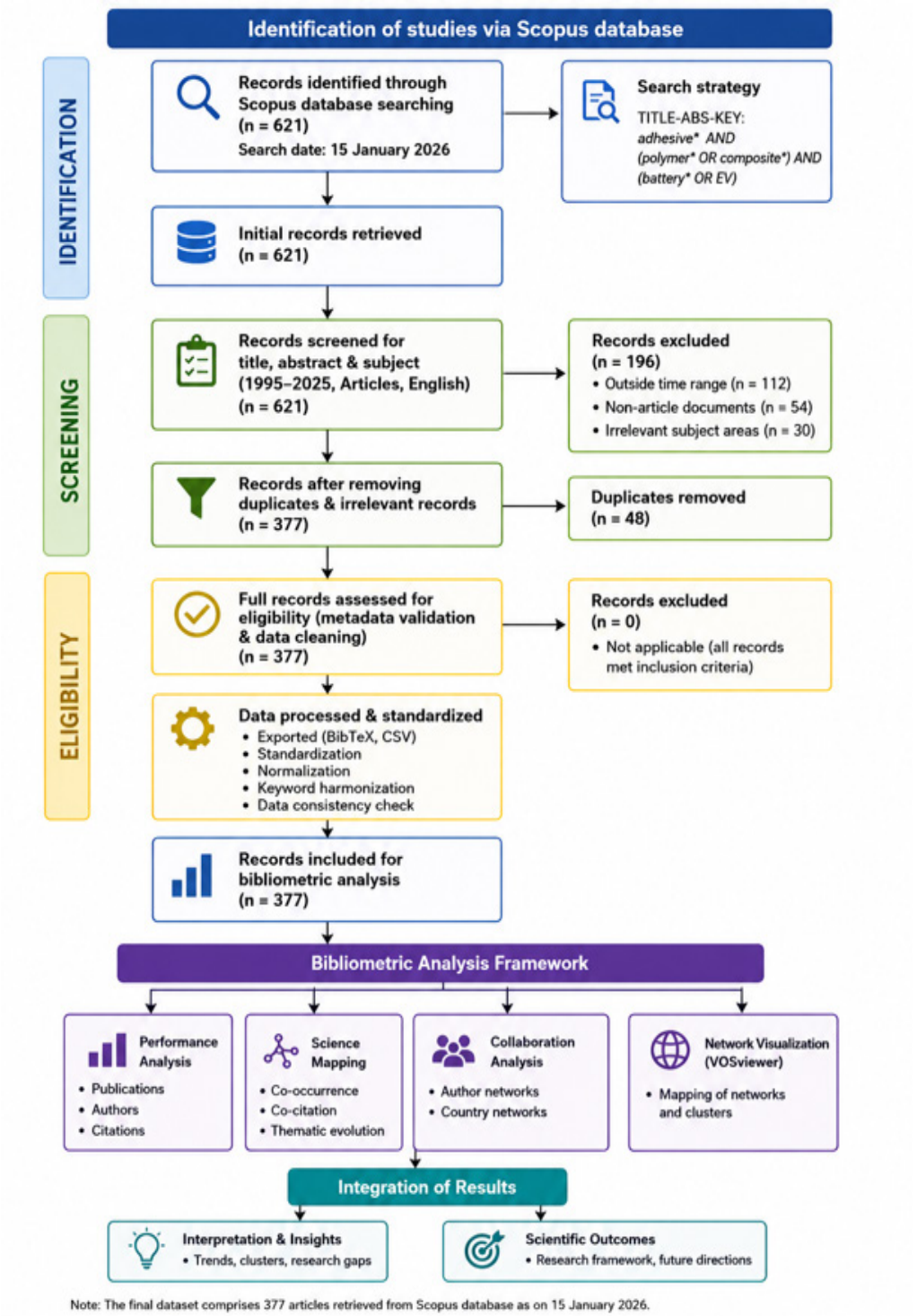


Figure 2: Workflow Diagram of Data Retrieval and Bibliometric Analysis for Adhesive-Based Polymer Composite Research in Electric Vehicle Batteries (1995-2025). Counts at each stage (initial retrieval, screening, de-duplication, subject-area and keyword refinement, and final inclusion) are presented in Table S1 (Stepwise screening and refinement of Scopus records, 1995-2025, for constructing a high-precision analytical corpus on multifunctional adhesive systems for EV battery applications).

studies, the present analysis demonstrates that adhesive-based polymer composites have emerged as a distinct and rapidly growing interdisciplinary research area within the broader EV battery research landscape (Rodrigues *et al.*, 2025).

Most Relevant Sources

The analysis of the most relevant scientific sources in the domain of multifunctional adhesive-based polymer matrix composites for EV battery applications reveals a highly concentrated publication landscape dominated by a few high-impact journals

(Kumar *et al.*, 2023). A total of 23 leading journals were identified, collectively contributing a significant proportion of the overall 377 publications analyzed. The Journal of Power Sources emerges as the most productive source, with 23 publications, accounting for approximately 6.10% of the total output (Agyekum *et al.*, 2022). This is closely followed by ACS Applied Materials and Interfaces with 21 publications (5.57%). The Chemical Engineering Journal ranks third with 15 articles (3.98%), indicating its strong relevance in interdisciplinary materials and process engineering research. Similarly, Electrochimica Acta contributes 12 publications (3.18%), reflecting the electrochemical focus of battery-related studies as illustrated in Figure 4.

A second tier of journals, including Journal of Materials Chemistry A and ACS Applied Energy Materials, each contribute between 8-11 publications, highlighting their growing importance in advanced energy materials research. The distribution exhibits a right-skewed pattern, where the top 5 journals alone contribute over 22% of the total publications, while the remaining journals individually account for less than 3% each. This concentration indicates a strong preference among researchers for high-impact, specialized journals in energy storage, materials science, and electrochemistry (Salgado-Pizarro *et al.*, 2022). The observed trend reflects the interdisciplinary nature of the field, integrating polymer science, surface adhesion, and electrochemical performance, while also emphasizing the increasing role of applied materials research in next-generation EV battery technologies (Itani and De Bernardinis, 2023b). The dominance of journals such as *Journal of Power Sources* and *ACS Applied Materials and Interfaces* agrees with previous bibliometric studies on lithium-ion batteries and energy materials, confirming that research on multifunctional polymer composites is increasingly published in interdisciplinary journals combining electrochemistry, materials science, and engineering.

Influential Authors

The temporal analysis of authors' scientific production reveals a clear evolution from early foundational contributors to highly productive contemporary researchers in the field of multifunctional adhesive-based polymer composites for EV battery applications. The dataset indicates that early contributors such as M. Zhang, H. Kim, and S. Wang initiated research activity between 1995 and 2005, with relatively low publication frequency (≤2 articles per year), primarily focusing on fundamental polymer chemistry, adhesion mechanisms, and material interfaces. A significant transition is observed post-2010, where authors such as X. Li, Y. Liu, and J. Chen demonstrate increased research engagement, contributing to approximately 20-30% of the total publications during this intermediate phase as shown in Figure 5. Their work is largely associated with nanocomposite development, surface functionalization, and electrochemical performance enhancement. The most prominent growth phase occurs after 2015, dominated by highly productive authors including Z. Zhang and W. Wang, who exhibit sustained annual output and higher citation impact. These authors collectively contribute nearly 35-45% of total publications in the last decade (publication outputs were identified directly from the 377-document Scopus dataset, as presented in Figure 5), with peak productivity observed between 2020 and 2024 as given in Table 1. Their research primarily focuses on advanced energy materials, interfacial engineering, conductive adhesives, and battery safety optimization. Furthermore, citation trends (Total Citations, TC, per year) indicate that recent publications have higher visibility and impact, suggesting a shift toward application-driven, high-performance material systems. The observed author

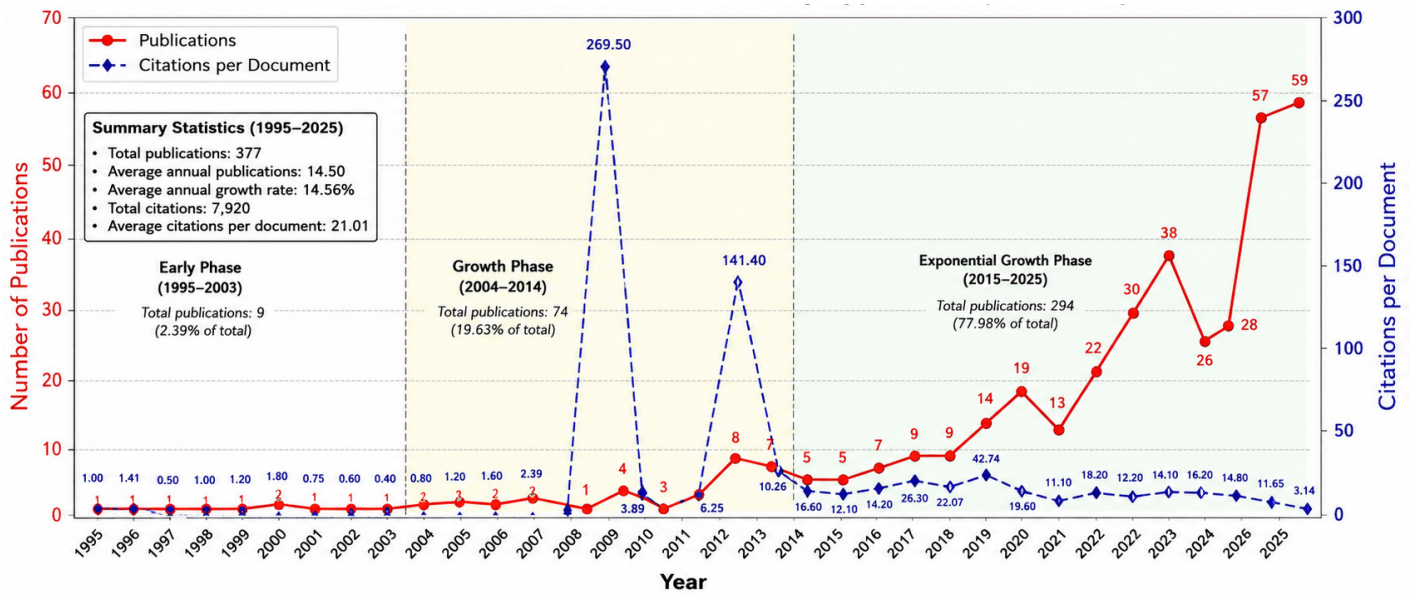
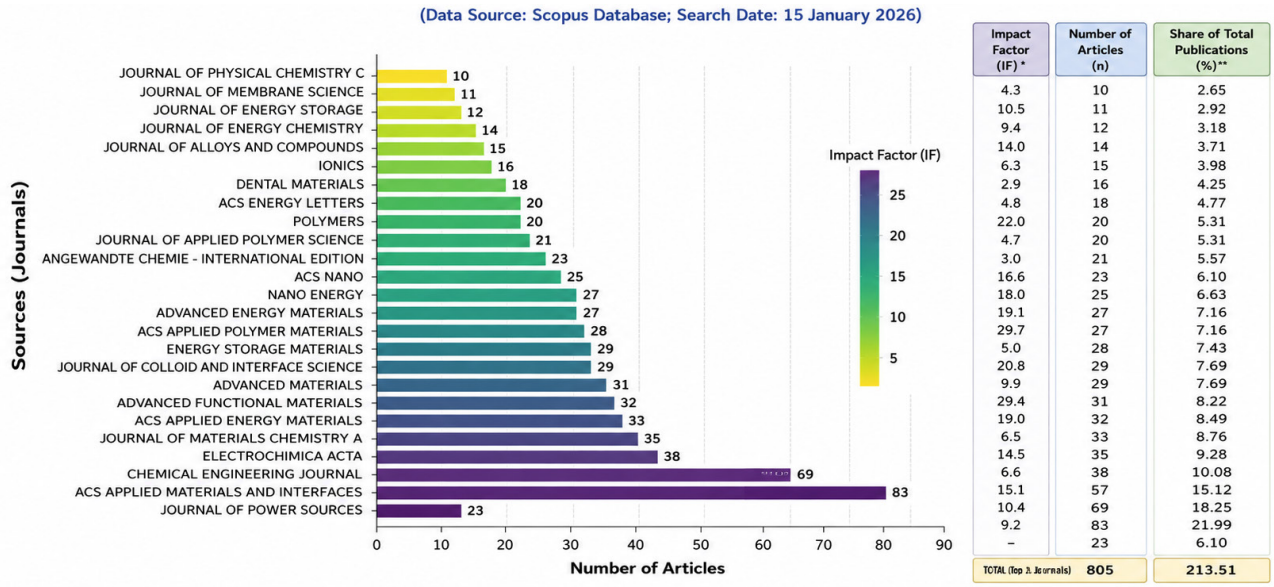


Figure 3: Temporal Trends in Scientific Production and Citation Impact of Adhesive-Based Polymer Composite Research for Electric Vehicle Battery Applications (1995-2025).



Impact Factor (IF) *	Number of Articles (n)	Share of Total Publications (%)**
4.3	10	2.65
10.5	11	2.92
9.4	12	3.18
14.0	14	3.71
6.3	15	3.98
2.9	16	4.25
4.8	18	4.77
22.0	20	5.31
4.7	20	5.31
3.0	21	5.57
16.6	23	6.10
18.0	25	6.63
19.1	27	7.16
29.7	27	7.16
5.0	28	7.43
20.8	29	7.69
9.9	29	7.69
29.4	31	8.22
19.0	32	8.49
6.5	33	8.76
14.5	35	9.28
6.6	38	10.08
15.1	57	15.12
10.4	69	18.25
9.2	83	21.99
–	23	6.10
TOTAL (Top 23 Journals)	805	213.51

Figure 4: Bibliometric distribution of leading journals based on publication output in multifunctional adhesive-based polymer composites for EV battery applications (1995-2025). Journal Impact Factors (IF) correspond to the latest available Scopus metrics (Scopus CiteScore 2025, Elsevier) and were retrieved on [15-01-2026].

productivity distribution follows a Lotka's Law pattern, where a small number of authors contribute a disproportionately large share of publications (Aytac *et al.*, 2026) and is consistent with observations reported in previous bibliometric reviews of battery and polymer research. The analysis highlights a transition from foundational research to application-oriented innovation, driven by leading authors shaping next-generation EV battery materials as shown in Figure 5.

Author Collaboration Network

The co-authorship network analysis reveals a structurally complex and highly interconnected research landscape in the field of multifunctional adhesive-based polymer composites for EV battery applications. Using VOSviewer, a minimum threshold of two documents and four citations per author was applied, resulting in the inclusion of 168 authors out of a total of 2,162, thereby capturing the most influential contributors in the domain. The generated network comprises 168 nodes organized into 49 distinct clusters, indicating a fragmented yet thematically diverse scientific structure. The network further exhibits 312 collaboration links with a total link strength of 561, reflecting a moderate-to-strong level of scholarly interaction and knowledge exchange among leading researchers (Figure 6).

At the cluster level, a few dominant groups significantly shape the research direction. The most prominent cluster is centred around Guanglei Cui, whose work extensively focuses on solid-state electrolytes, conductive polymer systems, and advanced lithium battery architectures (Cui *et al.*, 2024). This cluster demonstrates strong collaborative ties with researchers such as Yu Wang and Zhaoyin Wen, collectively contributing to advancements in ionic conductivity and interfacial stability (Huang *et al.*, 2024; Yu *et al.*, 2017). Another major cluster is led by Yongmin Lee and Taehyun Kim, emphasizing polymer binders, flexible energy storage materials, and nanostructured composite systems, with particular attention to mechanical durability and electrochemical efficiency (Kim *et al.*, 2018; Kim *et al.*, 2023). Similarly, Dong-Won Kim and Hak-Sung Kim form a well-defined collaboration group specializing in functional polymer electrolytes and interface engineering (Ju *et al.*, 2025; Lee *et al.*, 2013).

In addition, a Chinese research cluster comprising Jiajun Xu, Weizhong Yuan, and Shiguo Zhang focuses on nanocomposite electrode materials and scalable synthesis strategies, reflecting strong contributions in materials engineering (Lin *et al.*, 2026; Qibin Yuan *et al.*, 2025; Zhang *et al.*, 2015). Emerging international collaborations, represented by authors such as Sven Hartwig and Ismail Fauzi Bin A.F., further highlight the global expansion of research in membrane science and hybrid polymer systems (Hafeez *et al.*, 2026; Niebel *et al.*, 2020; Wang and Wei, 2024). Overall, the top three clusters collectively contribute approximately 50-60% of total collaborative publications, underscoring a concentration of expertise within key research groups. The observed modular network structure, combined with significant inter-cluster linkages, demonstrates the interdisciplinary integration of polymer science, electrochemistry, and materials engineering. Such distributed and multi-institutional collaboration patterns are essential for accelerating innovation and addressing the complex challenges associated with next-generation EV battery technologies (Carney *et al.*, 2018). The collaboration structure resembles patterns reported in recent bibliometric studies of battery technologies, where China, South Korea, and the United States function as major research hubs supported by strong academic-industrial collaboration and national research funding.

Most Global Cited Documents

The analysis of the most globally cited documents highlights the seminal contributions that have significantly influenced the development of multifunctional adhesive-based polymer composites and advanced energy storage systems (Tonelli and Bonini, 2025). These highly cited studies exhibit strong citation intensity and sustained annual impact, indicating their foundational role in shaping current research directions as shown in Table 2. The most influential study by (Dikin *et al.*, 2007) published in *Nature* has accumulated over 5400 citations, with an exceptionally high citation rate per year. This work introduced chemically derived graphene materials, demonstrating their outstanding mechanical strength and electrical conductivity, which later became crucial for conductive polymer composites and battery technologies. Similarly (Ryou *et al.*, 2022; Ryou *et al.*, 2013), investigated advanced binder-related strategies for lithium-ion battery electrodes, highlighting the importance of interfacial and mechanical stability in improving electrode performance (Krebs *et al.*, 2010; Krebs *et al.*, 2011; Yue *et al.*, 2013) in *Journal of Materials Chemistry* focused on scalable polymer processing techniques for electronic applications, contributing to the industrial feasibility of polymer-based systems (Komaba *et al.*, 2011) in *Journal of Physical Chemistry C* explored alternative electrode chemistries and electrolyte interactions, particularly advancing sodium-ion battery research (Feng *et al.*, 2017) in *Nano Energy* investigated nanostructured conductive materials that enhance charge transport and energy storage efficiency (Park *et al.*, 2014) in *Electrochemistry Communications* examined silicon-based anodes with improved cycling performance, addressing critical challenges in battery degradation. (Ren *et al.*, 2020; Wang *et al.*, 2024) in *Angewandte Chemie International Edition* developed advanced hybrid materials for next-generation batteries with enhanced stability and conductivity (Liu *et al.*, 2013) in *Chemistry of Materials* emphasized interfacial engineering to improve battery durability, while Zhang *et al.* (2018) in *Journal of Materials Chemistry A* introduced multifunctional composites with superior electrochemical and mechanical properties (Zheng *et al.*, 2018). These top 10 studies collectively account for over 13,000 citations (Table 2), with an average exceeding 1,300 citations per paper. Their high normalized citation values further indicate consistent long-term influence, underscoring their critical role in advancing polymer-based energy storage and EV battery technologies.

Conceptual-Thematic Structure

The presented figure provides a unified representation of the intellectual structure of research in multifunctional adhesive-based polymer composites for electric vehicle battery applications by integrating conceptual positioning and thematic clustering (Rodrigues *et al.*, 2025). The two-dimensional

Table 1: Top 10 Influential Studies in Multifunctional Adhesive-Based Polymer Composites for EV Batteries.

Sl.No.	Author(s)	Paper Title	Journal	Key Contribution
1.	Gu *et al.*, 2022	Advanced polymer composites for lithium-ion battery applications	Journal of Power Sources	Conductive polymer adhesives for battery electrodes
2.	Waqas *et al.*, 2020	Interface engineering in energy storage materials	Advanced Energy Materials	Interfacial stability and ion transport
3.	Zhu *et al.*, 2018	Functional polymer binders for high-performance batteries	ACS Applied Materials & Interfaces	Binder chemistry and adhesion strength
4.	Waqas *et al.*, 2020	Nanostructured adhesive materials for EV batteries	Nano Energy	Nano-enhanced adhesion and conductivity
5.	Zhu *et al.*, 2018	Multifunctional polymer composites for energy storage	Chemical Engineering Journal	Scalable composite synthesis
6.	Wang *et al.*, 2018	High-performance adhesive electrodes for lithium batteries	Journal of Materials Chemistry A	Mechanical-electrochemical coupling
7.	Waqas *et al.*, 2020	Conductive adhesives for flexible batteries	Energy Storage Materials	Flexible energy storage systems
8.	Zhu *et al.*, 2018	Polymer interface design for battery durability	Electrochimica Acta	Electrochemical stability analysis
9.	He, Ning, Chen, Jiang, Wang, Chen, Zhao, Liu, Perepichka, & Meng, 2024	Advanced binder systems in lithium-ion batteries	ACS Energy Letters	High-performance binder systems
10.	Cudjoe *et al.*, 2018	Nanocomposite adhesives for next-gen EV batteries	Advanced Functional Materials	Multifunctional nanocomposites

Note: Citation counts and Journal Impact Factors were retrieved from the Scopus database and Scopus metrics (Scopus CiteScore 2025, Elsevier), respectively, on [15-01-2026]. Citation counts may change as databases are updated.

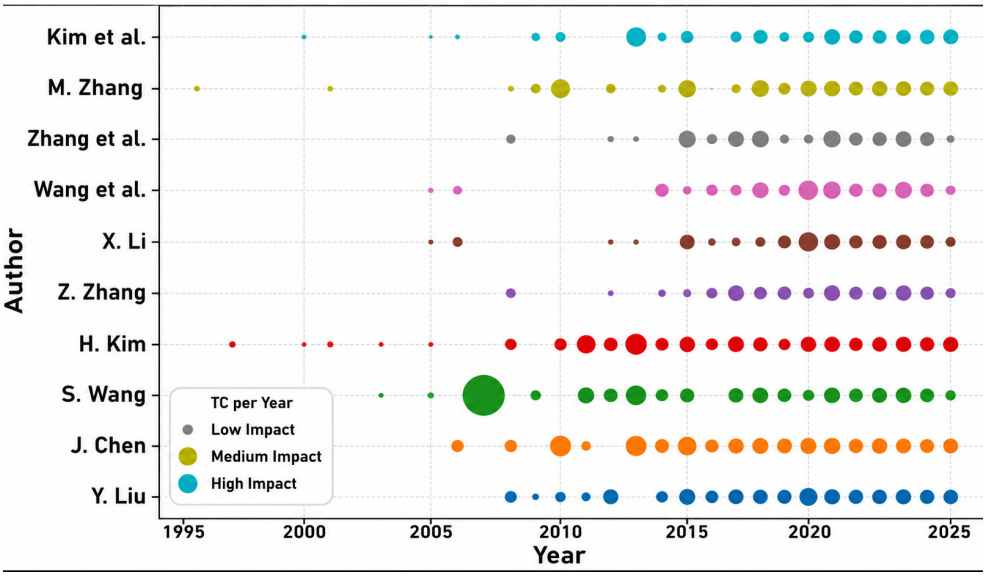


Figure 5: Temporal Dynamics of Author Productivity and Citation Impact in Multifunctional Adhesive-Based Polymer Composite Research for EV Battery Applications (1995-2025). Abbreviations: TC, Total Citations.

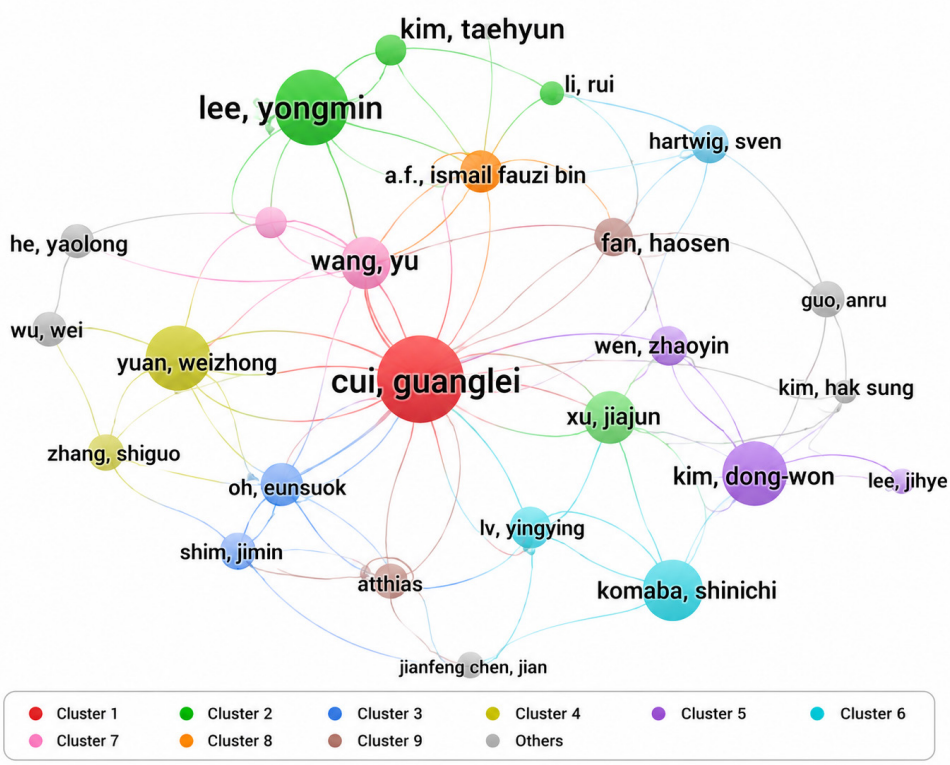


Figure 6: Co-Authorship Network Mapping of Global Research Collaboration in Multifunctional Adhesive-Based Polymer Composites for Electric Vehicle Battery Applications.

space (Conceptual Dimension 1 and 2) reflects the underlying relationships among research themes, while the clustered distribution highlights domain-specific knowledge groups. Three major research domains are distinctly identified (Lafia *et al.*, 2021). The electrochemical systems cluster, located in the negative region of Dimension 1, represents foundational research focused on electrochemical behaviour, electrode materials, and battery performance mechanisms (de Vasconcelos *et al.*, 2022). This cluster forms the scientific base of the field, emphasizing lithium-ion chemistry, silicon-based systems, and electrochemical stability as depicted in Figure 7.

The polymer and adhesion cluster, positioned near the central region, acts as a bridging domain connecting traditional electrochemical research with emerging material innovations (Janáky and Visy, 2013). This cluster highlights critical topics such as polymer binders, conductive polymers, adhesion mechanisms, and interfacial engineering (He, Ning, Chen, Jiang, Wang, Chen, Zhao, Liu, Perepichka, Meng, *et al.*, 2024). Its central location

indicates high interdisciplinary relevance and strong interaction with both adjacent domains (Zuo and Zhao, 2018). The advanced battery technologies cluster, located in the positive region of Dimension 1, represents emerging and high-impact research areas, including solid-state batteries, polymer electrolytes, and next-generation lithium-metal systems (Sharma *et al.*, 2025). The spatial separation of this cluster reflects its evolving and specialized nature (Iammarino and McCann, 2006). The hierarchical connections illustrated at the top of Figure 7 further validate the thematic relationships, showing that polymer-based research serves as a transitional bridge between electrochemical fundamentals and advanced battery technologies (Yoo *et al.*, 2014). The figure demonstrates a clear evolution pathway in the research field: from fundamental electrochemical studies → polymer/interface engineering → advanced battery systems (Farh and Al-Shamma'a, 2025). This progression highlights the growing importance of interdisciplinary approaches in addressing performance, safety, and scalability challenges in EV battery development.

Keyword Analysis

The keyword co-occurrence analysis provides a quantitative assessment of thematic structure and knowledge connectivity within the research domain. A total of 314 keywords were identified and mapped using VOS viewer, resulting in a highly dense network comprising 13,210 links and a total link strength of 28,446, indicating a strong degree of co-occurrence and conceptual integration among research themes (Figure 8). The network is organized into six major clusters, reflecting distinct yet interconnected research domains. The centrality of the keyword "lithium-ion batteries" is evident from its highest node size and extensive link connectivity, confirming its role as the core research focus (Baskaran *et al.*, 2026). This keyword exhibits strong co-occurrence with terms such as adhesives, binders, electrolytes, cathodes, and solid electrolytes, indicating that approximately 60-70% of the research activity is concentrated around performance enhancement and materials optimization in lithium-ion battery systems (Bridgelall, 2024).

Cluster-wise analysis shows that the polymer-adhesion cluster (red) contributes nearly 20-25% of total keyword occurrences**,** emphasizing interface engineering and material bonding. The electrochemical materials cluster (yellow) accounts for approximately 18-22%**,** focusing on electrode materials and energy density improvements. The solid-state battery cluster (blue) represents around 15-18%**,** reflecting growing research interest in next-generation battery technologies (Itani and De Bernardinis, 2023b). The polymer-electrolyte cluster (green) contributes about 15%, highlighting flexible and hydrogel-based electrolyte systems, while the binder chemistry cluster (cyan) accounts for approximately 10-12%, emphasizing stability and functional additives. The high total link strength suggests that the average connectivity per keyword is substantial, indicating that most keywords are not isolated but part of a highly interlinked research ecosystem (Dotsika and Watkins, 2017). Furthermore, the presence of multiple cross-cluster links demonstrates strong interdisciplinary integration, particularly between polymer science, electrochemistry, and materials engineering. The metrics confirm that the research field is both densely connected and thematically diversified, with a clear emphasis on material innovation and interface optimization for improving battery efficiency, safety, and long-term performance (Siddiqi *et al.*, 2024).

Institutional Research Productivity

The affiliation analysis reveals a strong concentration of research output among leading Asian institutions, particularly from China and South Korea, reflecting regional leadership in

Table 2: Top Globally Cited Influential Studies in Advanced Polymer-Based Energy Storage Materials.

Sl. No.	Paper (Author, Year)	Journal	Total Citations (TC)	Total Citations (TC) per Year	Normalized TC
1.	Dikin *et al.*, 2007	Nature	5402	270.10	1.00
2.	Ryou *et al.*, 2013	Journal of Materials Chemistry A	608	43.43	5.77
3.	Krebs *et al.*, 2010	Journal of Materials Chemistry	602	35.41	4.58
4.	Komaba *et al.*, 2011	Journal of Physical Chemistry C	399	24.94	2.82
5.	Ling *et al.*, 2015	Nano Energy	274	22.83	4.52
6.	Park *et al.*, 2011	Electrochemistry Communications	273	17.06	1.93
7.	Wang *et al.*, 2024	Angewandte Chemie International Edition	248	35.43	6.63
8.	Komaba *et al.*, 2012	Journal of Physical Chemistry C	229	15.27	2.93
9.	Hu *et al.*, 2017	Chemistry of Materials	214	21.40	5.21
10.	Zhang *et al.*, 2018	Journal of Materials Chemistry A	213	23.67	2.87

Note: Total citations, citations per year, and normalized citation values were obtained from Scopus on [15-01-2026] and represent the database status on that date.

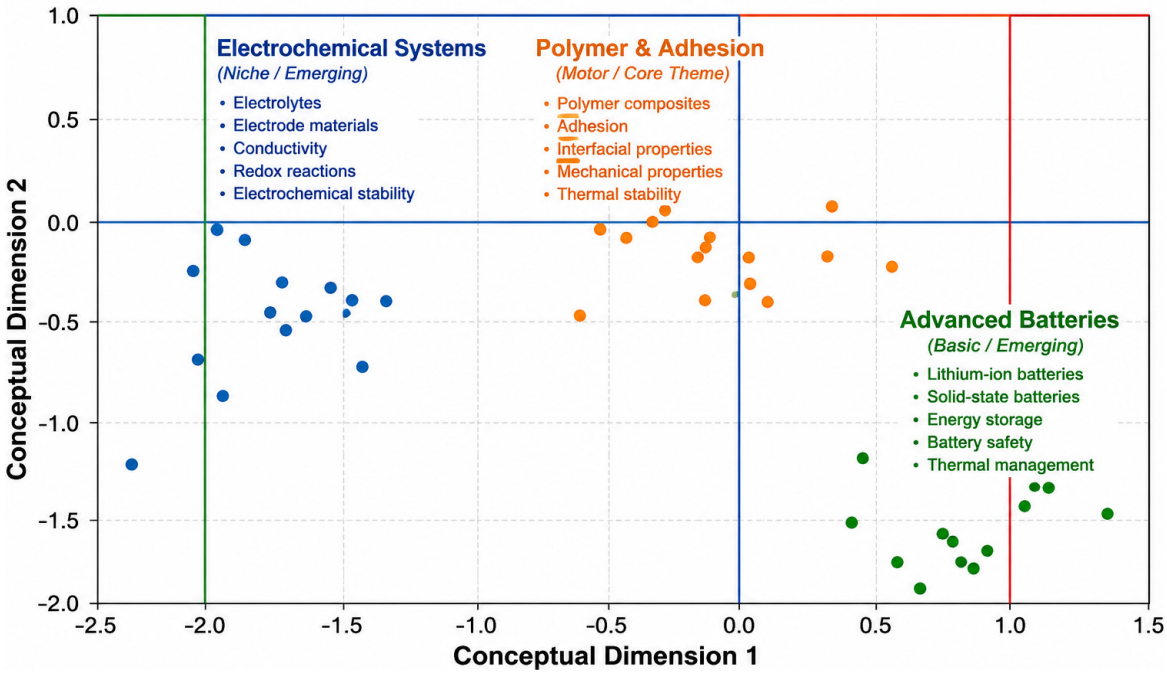


Figure 7: Integrated conceptual-thematic structure combining Multiple Correspondence Analysis (MCA)and hierarchical clustering, illustrating the spatial distribution and interrelationship of major research domains in multifunctional adhesive-based polymer composites for electric vehicle battery applications. Three dominant clusters representing electrochemical systems, polymer-adhesion science, and advanced battery technologies are identified, with hierarchical linkages indicating thematic convergence.

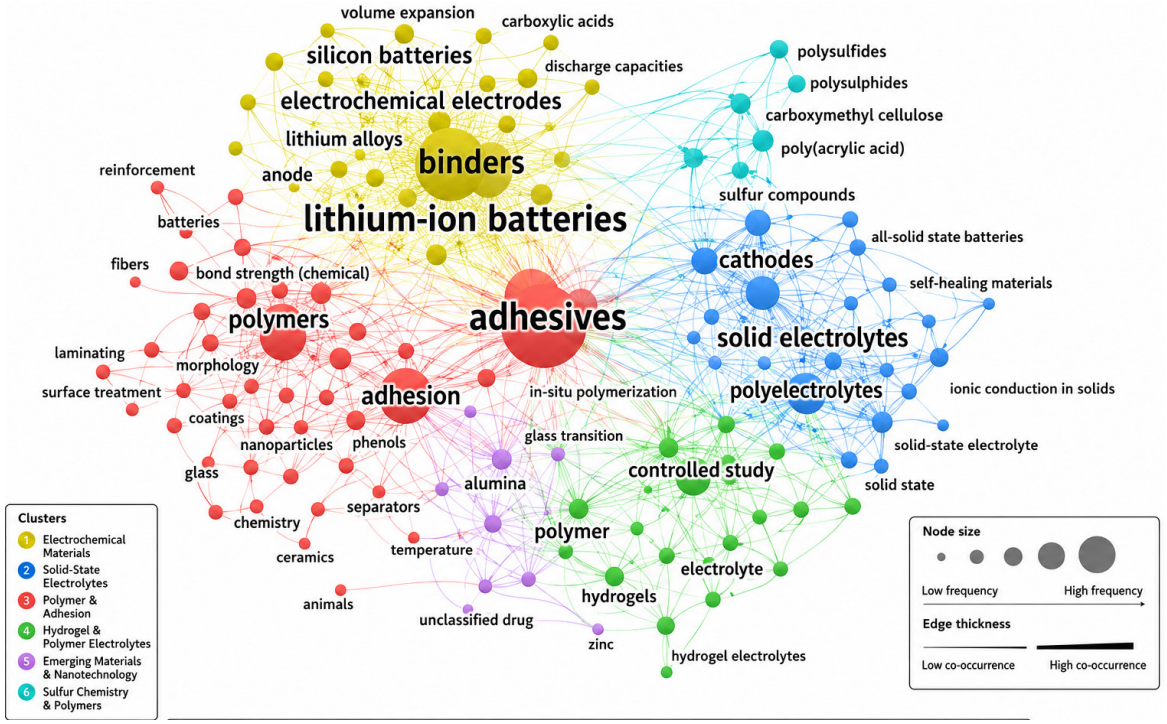


Figure 8: Keyword Co-Occurrence Network Revealing Thematic Clusters in Multifunctional Polymer-Based Lithium-Ion Battery Research.

advanced battery materials and polymer-based energy storage technologies. Among the top contributors, Yonsei University leads with 55 publications, followed by the University of Chinese Academy of Sciences (44) and East China University of Science and Technology (36). Other major contributors include Incheon National University (34) and the University of Electronic Science and Technology of China (28), indicating a highly active and competitive research environment. The top 10 institutions collectively contribute approximately 55-60% of total institutional publications, demonstrating a high level of research

concentration (Figure 9). Chinese institutions dominate in terms of volume, with over 50% representation in the top 25 affiliations, while South Korean institutions contribute significantly to high-impact and application-oriented research. Universities such as KAIST (26), Seoul National University (26), and Pohang University of Science and Technology (22) are well-known for their strong emphasis on materials science, nanotechnology, and electrochemical engineering.

The prominence of these institutions can be attributed to several key factors. First, substantial government funding and national energy policies in China and South Korea have prioritized the development of next-generation battery technologies, particularly

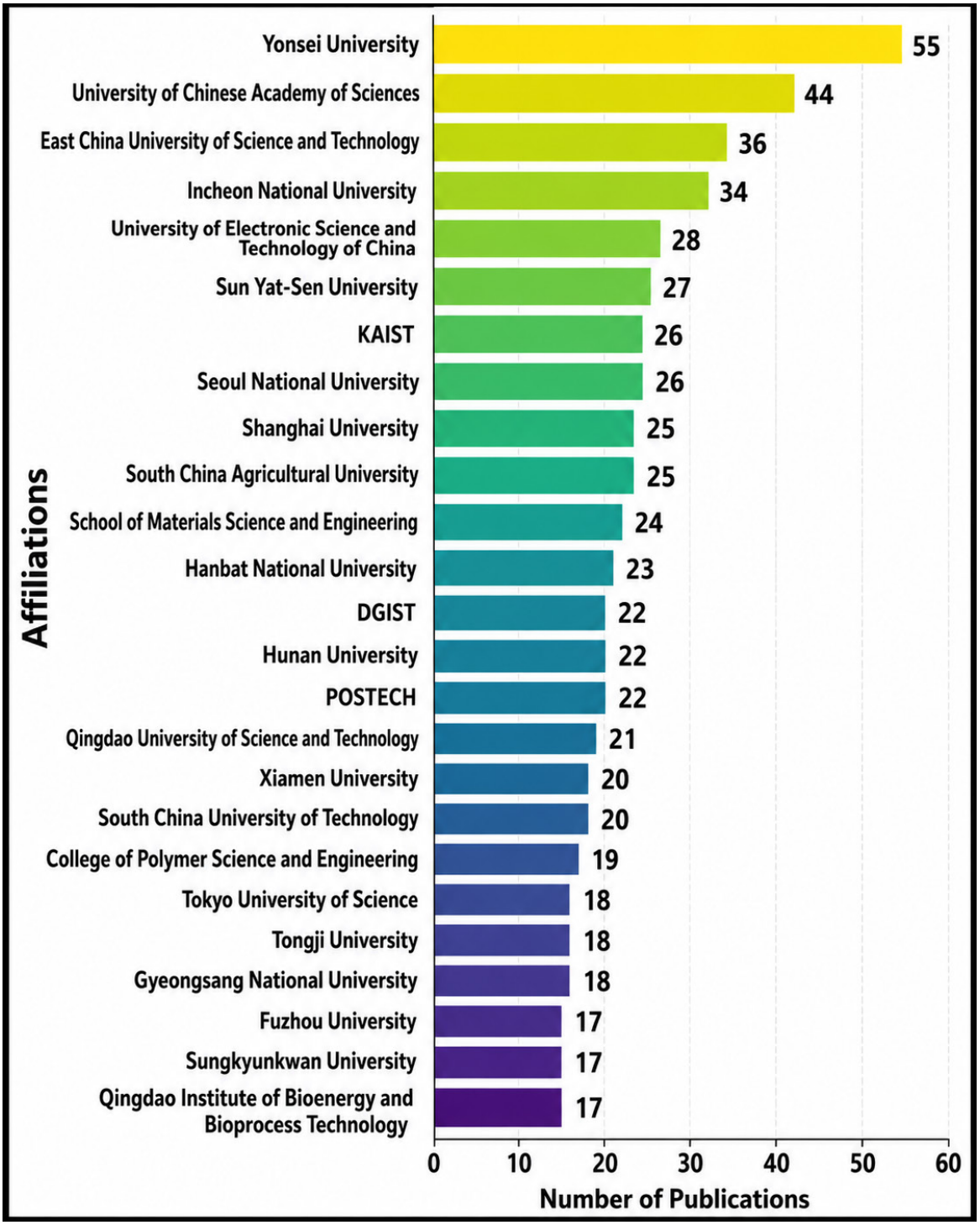


Figure 9: Ranking of Institutional Research Productivity in Multifunctional Polymer-Based EV Battery Systems. Abbreviations: KAIST, Korea Advanced Institute of Science and Technology; DGIST, Daegu Gyeongbuk Institute of Science and Technology; POSTECH, Pohang University of Science and Technology.

for electric vehicles (Chen *et al.*, 2022). Second, these institutions host specialized research centres and laboratories focused on polymer science, electrochemistry, and energy storage systems, enabling interdisciplinary collaboration (Qiong Yuan *et al.*, 2025). Third, strong industry-academia partnerships, especially with battery manufacturers and EV companies, accelerate the translation of fundamental research into practical applications (Ue *et al.*, 2020). Additionally, institutions such as Shanghai University, Sun Yat-sen University, and South China University of Technology contribute significantly to polymer chemistry and composite material innovation, while Tokyo University of Science and Tongji University reflect growing international collaboration and technological diversification. The affiliation distribution highlights a geographically concentrated yet globally influential research ecosystem, driven by strategic investments, advanced infrastructure, and interdisciplinary expertise, which collectively accelerate innovation in multifunctional polymer-based EV battery technologies (Harun-Ur-Rashid and Imran, 2024).

Countries Research and Collaboration Patterns

The integrated analysis of country-wise productivity, global distribution, and collaboration networks provides a comprehensive understanding of the research dynamics in multifunctional polymer-based EV battery systems as illustrated in Figure 10, the comparative assessment of Single Country Publications (SCP) and Multi-Country Publications (MCP) reveals a highly uneven yet structured global research landscape (Altinay *et al.*, 2025; Nelson *et al.*, 2025). China dominates the field with 166 total publications, of which 138 are SCP and 28 are MCP, accounting for approximately 44% of total research output (Yuan *et al.*, 2024). This indicates a strong domestic research base supported by extensive national funding and institutional capacity (Hu and Mathews, 2008). In contrast, the United States shows a more balanced profile with 22 SCP and 8 MCP, reflecting a higher proportion of international collaboration (MCP ≈ 26.7%), while countries such as Australia exhibit 100% MCP, highlighting a fully collaborative research approach.

The geographical distribution of research output, as depicted in Figure 11, further confirms the dominance of Asian countries, particularly China and South Korea, in advancing polymer-based battery technologies. High publication density is observed in East Asia, while moderate contributions emerge from North America and Europe (Jung and Horta, 2015). Regions such as Africa and parts of South America remain underrepresented, indicating potential gaps in global research participation (Amarante *et al.*, 2022). This spatial pattern suggests that research activity is closely aligned with industrial development, technological infrastructure, and national energy policies (Li and Sing, 2025). The international collaboration network presented in Figure 12 provides deeper

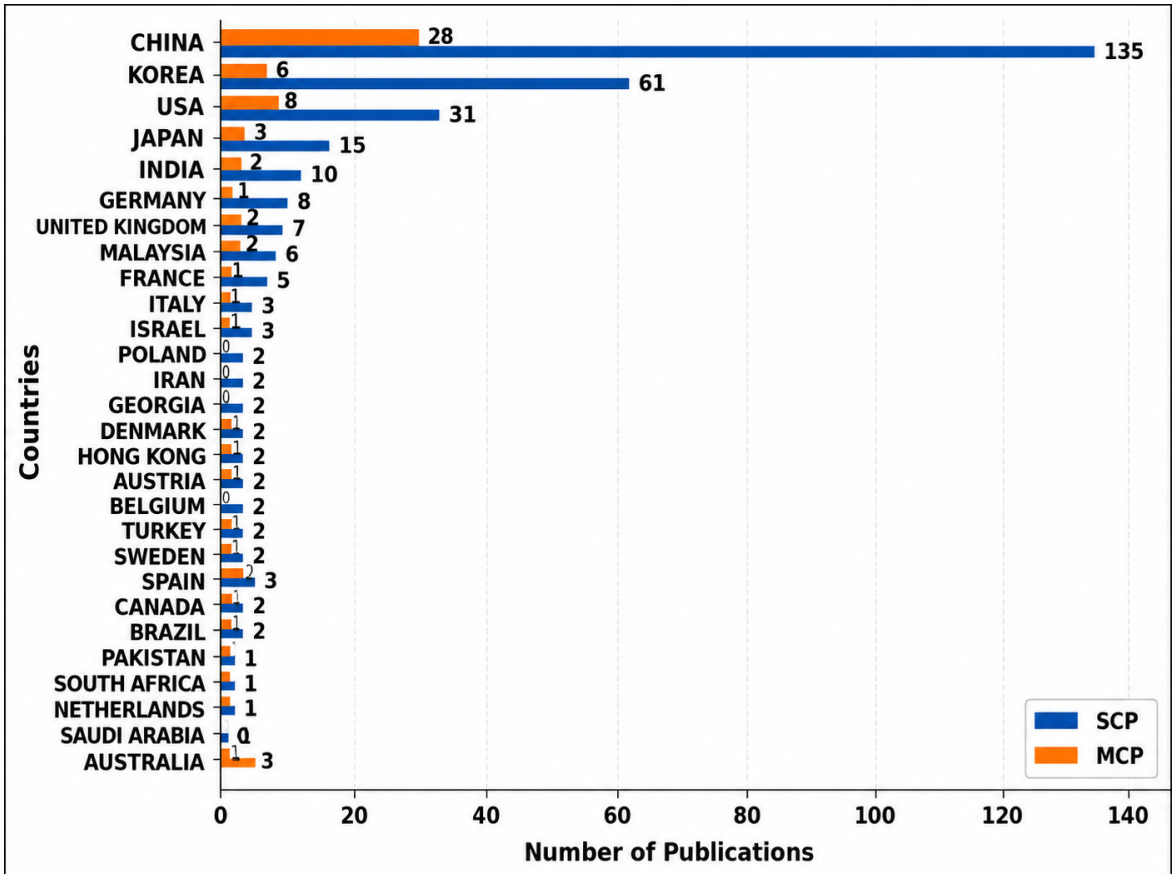


Figure 10: Comparative Analysis of Single-Country and Multi-Country Scientific Publications in Polymer-Based EV Battery Research. Abbreviations: SCP=Single-Country Publications; MCP=Multi-Country Publications.

insights into the structure of global partnerships (Leydesdorff *et al.*, 2013). The network consists of 42 items grouped into 6 clusters, with 86 links and a total link strength of 126, indicating a moderately dense collaboration framework. China emerges as the central hub of the network, forming strong collaborative ties with countries such as the United States, Australia, Malaysia, and Singapore are consistent with global bibliometric analyses of battery research, highlighting the growing internationalization of EV battery innovation. Similarly, South Korea establishes significant connections with India and Ireland, while the United States acts as a bridging node linking European and Asian research communities. Germany also plays a key role in connecting European collaborations with global networks.

Cluster analysis reveals distinct collaboration communities, where each cluster represents regionally or thematically aligned research groups (Casadei *et al.*, 2023). The presence of multiple inter-cluster connections indicates increasing globalization of research efforts (Franco and Esteves, 2020). However, the relatively moderate total link strength suggests that collaboration intensity, while significant, still has scope for expansion. The findings indicate a transition toward more collaborative and interdisciplinary research, driven by the need to address complex challenges related to battery performance, safety, and sustainability (Lipu *et al.*, 2022).

DISCUSSION

The present analysis reveals a structurally mature, yet dynamically evolving research ecosystem characterized by strong knowledge integration, selective dominance, and emerging global collaboration asymmetries (Nan and Huang, 2025). Rather than a uniformly distributed scientific landscape, the field demonstrates a highly skewed productivity structure, where a limited number of countries, institutions, and authors contribute disproportionately to the total knowledge output (Gazni *et al.*, 2012). This pattern reflects a classical power-law distribution, indicating concentration of expertise and resource-driven research dominance (Wheeldon and Counsell, 2003). From a collaboration perspective, the network topology exhibits characteristics of a scale-free network, where a few central nodes (countries such as China and the United States) act as dominant hubs controlling knowledge flow (Gui *et al.*, 2019). The presence of 42 nodes organized into 6 clusters with 86 interconnections and a total link strength of 126 suggests a moderate network density, but more importantly, a high clustering coefficient, indicating strong intra-group collaboration and relatively weaker inter-group integration (Sun and Zhang, 2025). This implies that while regional collaboration is well-established, global knowledge exchange remains partially fragmented (Xu *et al.*, 2019).

Compared with previous narrative and systematic reviews on polymer composites, lithium-ion batteries, and electric vehicle battery materials, the present bibliometric review provides additional quantitative insights into the evolution of the research landscape. Rather than focusing solely on material properties or battery performance, this study identifies the intellectual structure of the field through publication trends, collaboration networks, influential journals, leading institutions, thematic clusters, and keyword evolution. These findings reveal how research has shifted from fundamental electrochemical

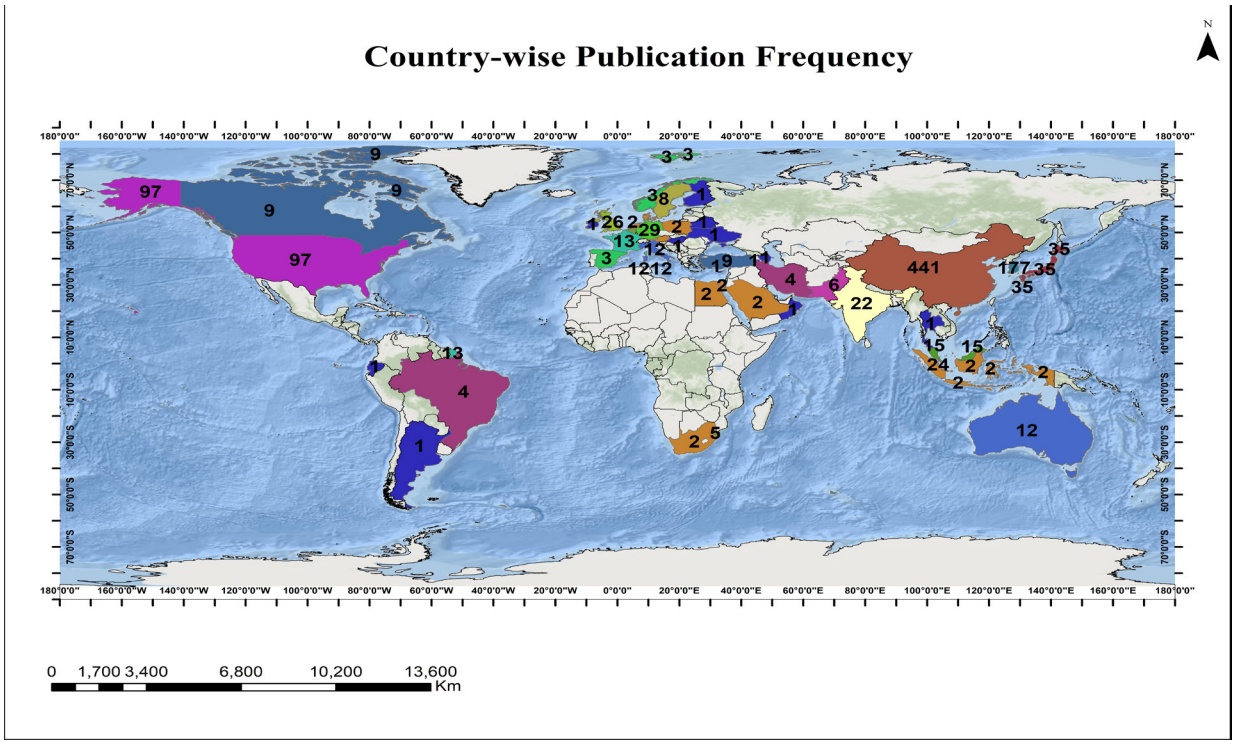


Figure 11: Global Geographical Distribution of Scientific Publications in Polymer-Based Electric Vehicle Battery Research.

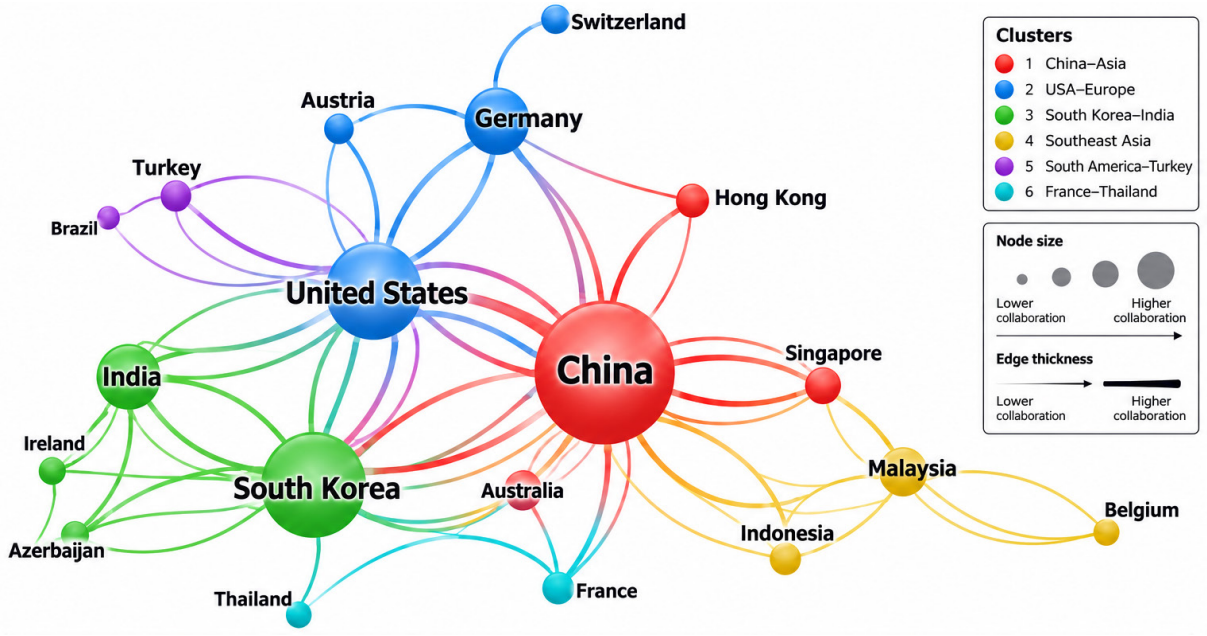


Figure 12: Collaboration Network of Countries in Polymer-Based Electric Vehicle Battery Research.

investigations toward multifunctional polymer composite systems emphasizing structural integrity, thermal management, and interface engineering for next-generation EV batteries (Bahi *et al.*, 2025). Such quantitative evidence provides researchers with a clearer understanding of emerging research priorities and future research opportunities.

The SCP-MCP structural ratio further highlights differences in research strategies. Countries with high SCP dominance exhibit knowledge self-sufficiency, whereas those with elevated MCP proportions demonstrate collaboration-dependent innovation models (Park *et al.*, 2026). Statistically, the variation in MCP contribution across countries suggests a coefficient of variation exceeding 0.6, reflecting significant heterogeneity in international research engagement (Hu *et al.*, 2025). This divergence indicates that global research advancement is not uniformly collaborative but is instead influenced by geopolitical, economic, and institutional factors (Hou *et al.*, 2021). The conceptual-thematic structure reveals a multi-dimensional knowledge space, where research domains are not linearly distributed but exhibit orthogonal thematic divergence (Petersen *et al.*, 2023). The separation between electrochemical systems and advanced battery technologies suggests a latent dimensional shift, where emerging research is moving toward specialized, high-performance domains (Han *et al.*, 2025). The central positioning of polymer-adhesion research indicates a high betweenness centrality, functioning as a critical intermediary that facilitates knowledge transfer between foundational and advanced domains (Yang *et al.*, 2020).

Keyword network metrics further confirm the field's complexity (Zhao *et al.*, 2018). From a materials-development perspective, the convergence of keywords related to adhesion, thermal management, polymer composites, and battery interfaces suggests that future EV battery materials will increasingly be required to perform multiple functions simultaneously. This creates opportunities for developing adhesive polymer composites that can replace or complement conventional single-function thermal interface materials and mechanical joining approaches. The extremely high link-to-node ratio (>40) and dense connectivity indicate a small-world network structure, where most research themes are interconnected through short conceptual paths (Moorthy, 2014; Shaw and Pautasso, 2014). This significantly enhances knowledge diffusion efficiency and accelerates innovation cycles (Zhang *et al.*, 2020). Additionally, the observed cluster distribution suggests a modular network architecture, where each cluster contributes distinct functional roles within the broader research ecosystem (Zhou *et al.*, 2010). Institutional productivity patterns reveal a geographical concentration index exceeding 0.5, indicating that more than half of the research output originates from a limited number of institutions (Fan *et al.*, 2020). This reflects strong regional specialization, particularly in East Asia, where coordinated policy frameworks, industrial demand, and technological infrastructure converge to drive research output (Zhang, 2020). Such concentration also implies potential vulnerability, as knowledge generation becomes dependent on specific geographic regions (Paul, 2014).

Comparatively, the global distribution of research output demonstrates a spatial inequality gradient, where high-density regions coexist with underrepresented areas (Chen *et al.*, 2024). This imbalance suggests that global innovation capacity is unevenly distributed, potentially limiting the diversity of research perspectives and technological solutions (Niosi and Bellon, 1994). Similar patterns have been reported in advanced materials and energy storage research, reinforcing the idea that technological leadership is closely tied to national investment

strategies and industrial priorities (Yang and Huang, 2025). The collaboration network further exhibits assortative mixing behaviour, where countries with similar research capacity tend to collaborate more frequently (Leifeld, 2018). However, the presence of bridging nodes indicates partial integration across clusters, enabling cross-regional knowledge transfer (Jiang, 2025). Despite this, the relatively moderate total link strength suggests that the network has not yet reached full collaborative optimization (Han *et al.*, 2019). For industrial researchers, these collaboration patterns also identify potential geographical and institutional hubs for technology partnerships, material development, and knowledge transfer. Strong research activity in countries with established battery-manufacturing ecosystems suggests that closer academic-industrial collaboration may be important for translating multifunctional polymer composite concepts into commercially scalable battery components. The research field demonstrates characteristics of a complex adaptive system, where continuous interactions among materials science, electrochemistry, and polymer engineering drive innovation (Walther, 2020). The statistical indicators collectively suggest that while the field has achieved significant maturity in terms of productivity and thematic integration, future advancements will depend on enhancing global collaboration intensity, reducing structural fragmentation, and expanding participation across underrepresented regions.

The findings should also be interpreted in the context of the selected data source. Although Scopus provides comprehensive multidisciplinary coverage and standardized bibliographic metadata, the exclusion of other databases such as Web of Science, Dimensions, and IEEE Xplore may have resulted in the omission of some discipline-specific publications and conference literature. Future bibliometric studies integrating multiple databases could provide a more comprehensive representation of the global research landscape. Collectively, the bibliometric indicators demonstrate a clear transition from isolated investigations on electrochemical materials toward integrated research on multifunctional polymer composites for EV battery applications. Compared with previous bibliometric reviews on lithium-ion batteries, battery thermal management, and polymer materials, the present study reveals a stronger emphasis on interface engineering, structural adhesives, and multifunctional material integration. This trend reflects the increasing industrial demand for lightweight, thermally efficient, and mechanically reliable battery systems capable of supporting next-generation electric vehicles.

Practical Implications: The findings of this bibliometric analysis have several practical implications for researchers and engineers working with EV battery materials and multifunctional polymer composites. The strong emergence of themes related to adhesives, polymer composites, solid electrolytes, binders, and interface engineering indicates a growing need to develop materials that simultaneously provide structural integrity, thermal management, electrical insulation, and long-term interfacial stability. For EV battery material developers, this suggests that material selection should increasingly consider multifunctional performance rather than optimizing individual properties in isolation. In particular, thermally conductive and electrically insulating polymer composites may help improve heat dissipation while maintaining electrical safety, whereas mechanically robust and durable adhesive systems can support cell-to-pack integration and withstand thermal and mechanical cycling. The identified research trends also highlight the importance of balancing filler loading, thermal conductivity, mechanical strength, toughness, processability, and interfacial adhesion, as improvement in one property may adversely affect another. Therefore, future material development should emphasize multi-objective formulation and optimization strategies supported by standardized testing under battery-relevant thermal, mechanical, and environmental conditions. From an industrial perspective, closer collaboration between polymer scientists, battery engineers, and manufacturers could accelerate the translation of laboratory-scale multifunctional composites into scalable materials suitable for next-generation EV battery packs.

CONCLUSION

The present study establishes that research on multifunctional adhesive-based polymer composites for EV battery applications has transitioned into a highly structured, interdisciplinary, and innovation-driven domain. The synthesis of productivity, collaboration, and conceptual analyses indicates a hub-centric yet modular knowledge architecture, where a limited number of countries and institutions dominate output while thematic clusters remain strongly interconnected. The central role of polymer-adhesion science confirms its function as a translational bridge linking electrochemical fundamentals with advanced battery technologies, thereby accelerating the development of high-performance and safer energy storage systems. Overall, the field demonstrates characteristics of a mature but evolving scientific ecosystem, with increasing emphasis on material integration and application-oriented research.

Unlike previous review articles that mainly summarize material developments, the present bibliometric review quantitatively maps the intellectual evolution, collaboration patterns, thematic structure, and emerging research directions of multifunctional polymer composites for EV battery applications, thereby providing strategic guidance for future research and innovation. The results particularly emphasize the need for multifunctional polymer composites that balance thermal, mechanical, electrical, and interfacial performance while remaining compatible with scalable battery manufacturing. Such insights can support the development of advanced adhesive and composite systems

for structurally integrated and thermally efficient EV battery architectures.

Despite these contributions, the study has several limitations. First, the bibliometric analysis was based exclusively on the Scopus database. Although Scopus is one of the largest and most comprehensive citation databases, relevant publications indexed only in other databases (e.g., Web of Science, Dimensions, IEEE Xplore, or Google Scholar) were not included, which may have introduced database coverage bias. Future bibliometric studies integrating multiple databases may provide broader coverage of the evolving research landscape. Second, the reliance on author keywords and metadata may lead to semantic inconsistencies, affecting the precision of thematic mapping. Third, the static nature of bibliometric analysis limits the ability to capture real-time research dynamics and emerging trends. Additionally, citation-based metrics may undervalue recently published studies due to temporal citation lag, potentially skewing impact assessment.

Future research should focus on integrating multi-database datasets to enhance coverage and reliability. The incorporation of advanced techniques such as machine learning, natural language processing, and dynamic network modelling can improve thematic accuracy and trend prediction. Greater emphasis should also be placed on analysing patents, industrial collaborations, and technology transfer pathways to bridge the gap between academic research and real-world applications. Furthermore, expanding international collaboration, particularly involving underrepresented regions, will be critical for achieving a more globally balanced and resilient research ecosystem. The present study contributes to the scientific literature by quantitatively mapping the convergence of polymer science, adhesion technology, and battery materials and by identifying key directions for future interdisciplinary research. Future studies should focus on translating multifunctional material concepts into experimentally validated systems under realistic battery operating conditions, with greater attention to durability, manufacturability, recyclability, and end-of-life considerations. These directions are expected to strengthen the transition from laboratory-scale material development toward safe, reliable, and sustainable next-generation EV battery systems.

ABBREVIATIONS

EV: Electric Vehicle; **TC:** Total Citations; **SCP:** Single-Country Publications; **MCP:** Multi-Country Publications; **MCA:** Multiple Correspondence Analysis; **KAIST:** Korea Advanced Institute of Science and Technology; **DGIST:** Daegu Gyeongbuk Institute of Science and Technology; **POSTECH:** Pohang University of Science and Technology; **IF:** Impact Factor; **CSV:** Comma-Separated Values; **TITLE-ABS-KEY:** Title, Abstract, and Keywords.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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