Mapping the Research Landscape of Emerging Functionalization in Sulfonated Poly(Ether Ether Ketone) Proton Exchange Membrane: A Bibliometric Analysis

Haryani Mohd Yatim[1,2] and Juhana Jaafar[1]*
[1]Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[2]Advanced Membrane Technology Research Centre (AMTEC), Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
*Corresponding author (e-mail: juhana@petroleum.utm.my)

The development of efficient proton exchange membranes (PEMs) is critical for advancing fuel cell technologies, where sulfonated poly(ether ether ketone) (SPEEK) has emerged as a promising alternative to conventional perfluorosulfonic acid (PFSA) membranes. Hence, a systematic quantitative overview of global research on SPEEK functionalization is pressingly required. This study, therefore, conducts a bibliometric analysis of SPEEK-based PEMs research from 2005 to 2025 to evaluate its scientific development, structure, and emerging trends. The results presented strong and continuous growth in publications, particularly after 2015, indicating increasing global interest in SPEEK functionalization. The field is highly collaborative, with an average of 5.75 co-authors per document and a high citation impact (38.43 citations per document). Research output is concentrated in key journals such as the International Journal of Hydrogen Energy, Journal of Membrane Science, and Journal of Power Sources. China is the leading contributor, followed by India, Korea, Iran, and Malaysia. Thematic evolution indicates a shift from conventional SPEEK membranes toward multifunctional nanocomposite systems with improved durability and performance. Overall, the findings from the study offer valuable insights into research hotspots and future directions for developing high-performance proton exchange membranes for fuel cell applications.

Keywords: Sulfonated PEEK, Functionalization, Proton exchange membrane, Bibliometric analysis, PEMFC

Received: October 2025; Accepted: July 2026

The increasing demand for sustainable and clean energy technologies has accelerated the global transition from fossil fuel-based systems toward low-carbon energy solutions. Among various alternative energy technologies, hydrogen has emerged as a promising energy carrier due to its high energy density and environmentally benign conversion process[1]. In this context, proton exchange membrane fuel cells (PEMFCs) have attracted considerable attention because of their high energy conversion efficiency, rapid start-up, low operating temperature, and near-zero pollutant emissions [2, 3]. These advantages make PEMFCs highly suitable for transportation, portable electronics, and stationary power generation. Nevertheless, the overall performance, durability, and commercial viability of PEMFCs are strongly governed by the properties of the proton exchange membrane (PEM), which serves as the electrolyte responsible for proton transport while simultaneously preventing electron conduction and fuel crossover. Therefore, the development of high-performance PEM materials remains one of the most important research priorities for advancing fuel cell technology.

Perfluorosulfonic acid (PFSA) membranes, particularly Nafion®, have long been considered the benchmark electrolyte because of their excellent proton conductivity, mechanical strength and chemical stability when hydrated [4, 5]. However, their high production cost, restricted mechanical strength, high methanol permeability, low thermal and chemical stability and reduced performance at elevated temperatures have stimulated the search for alternative membrane materials [5]. Among numerous hydrocarbon polymers, sulfonated poly(ether ether ketone) (SPEEK) has emerged as one of the most promising candidates owing to its excellent thermal stability, mechanical strength, film-forming ability, tailorable degree of sulfonation, relatively low cost, and lower fuel permeability [6–8] Despite these advantages, pristine SPEEK membranes still suffer from several intrinsic limitations, including excessive water uptake, dimensional swelling, oxidative degradation, and the inherent trade-off between proton conductivity and membrane stability[6, 8–10]. These challenges have motivated extensive research into functionalization strategies aimed at simultaneously improving electrochemical

performance, mechanical integrity, and long-term durability.

Over the past two decades, research on SPEEK functionalization has expanded rapidly with the introduction of diverse modification approaches, including polymer blending, chemical crosslinking, grafting, incorporation of inorganic nanoparticles, carbon-based nanomaterials, metal–organic frameworks (MOFs), covalent organic frameworks (COFs), ionic liquids, and antioxidant additives [9, 11]. These strategies have been explored to enhance proton transport, reduce methanol crossover, improve water retention, strengthen mechanical properties, and mitigate oxidative degradation. Consequently, the research landscape has evolved from conventional membrane synthesis toward the design of multifunctional nanocomposite and hybrid membranes. The continuous emergence of new materials, fabrication techniques, and characterization methods has resulted in a substantial increase in scientific publications and interdisciplinary collaborations, making it increasingly challenging to obtain a comprehensive understanding of the field through conventional narrative reviews alone.

Bibliometric analysis has become a powerful quantitative approach for evaluating scientific development and mapping the intellectual structure of rapidly expanding research fields. Unlike traditional review articles that primarily synthesize experimental findings, bibliometric analysis objectively examines publication output, citation patterns, influential authors, productive institutions, collaborative networks, publication sources, and many others using bibliographic metadata [12]. Such analyses enable researchers to identify research hotspots, emerging trends, and knowledge gaps while providing a comprehensive overview of the evolution of a research field. Although bibliometric studies have been conducted on hydrogen energy, fuel cells [13] , electrocatalysts [14], and proton exchange membranes [15], a dedicated bibliometric assessment focusing specifically on emerging functionalization strategies in SPEEK-based proton exchange membranes remains unavailable. Consequently, the global development, collaboration patterns, and conceptual evolution of this research area have not been systematically explored.

To address this knowledge gap, the present study conducts a comprehensive bibliometric analysis of global research on emerging functionalization in SPEEK PEMs published between 2005 and 2025 using the Web of Science Core Collection (WoSCC) database. Bibliographic records were analysed using the Bibliometrix package and Biblioshiny interface to evaluate publication growth, leading journals, influential authors, productive institutions, contributing countries and keyword co-occurrence. By quantitatively mapping the scientific landscape of SPEEK functionalization research, this study provides a comprehensive overview of the field's historical development, identifies emerging research hotspots and collaboration patterns, and highlights future research opportunities. The findings offer valuable insights for researchers, material scientists, and policymakers seeking to accelerate the development of advanced proton exchange membranes for next-generation fuel cell applications.

METHODOLOGY

Data Source and Search Strategy

This study employed a bibliometric approach to systematically evaluate the global research landscape of emerging functionalization in SPEEK as proton exchange membranes for fuel cell applications. The bibliographic data were retrieved exclusively from the Web of Science Core Collection (WoSCC), one of the most authoritative and widely recognized scientific databases for bibliometric research. WoSCC was selected because it indexes high-quality peer-reviewed literature across multiple disciplines and provides standardized bibliographic information, including complete citation records, author affiliations, keywords, abstracts, funding information, and cited references. Compared with other scientific databases, WoSCC offers rigorous journal selection criteria, high-quality metadata, and excellent compatibility with bibliometric software such as Bibliometrix, making it a preferred data source for science mapping and performance analysis.

A comprehensive literature search was conducted in the WoSCC database to identify publications related to the functionalization of SPEEK as proton exchange membranes. The search strategy was developed using combinations of keywords associated with SPEEK, proton exchange membranes, fuel cells, and membrane functionalization. The search was performed using the Topic (TS) field, which simultaneously searches article titles, abstracts, author keywords, and Keywords Plus to maximize retrieval while maintaining the relevance of the dataset. The search string employed in this study was:

TS = (("sulfonated poly ether ether ketone" OR "SPEEK" OR "sulphonated poly ether ether ketone" OR "sulfonated PEEK") AND ("fuel cell " OR "fuel-cell system" OR "fuel-cell technology" OR "proton exchange membrane fuel cell" OR "polymer electrolyte fuel cell" OR "PEM Fuel Cell" OR "PEMFC" OR "PEFC system") AND ("functionalization" OR "functionalisation" OR "nanocomposite" OR "composite" OR "crosslink" OR "blending" OR "MOF" OR "COF" OR "HOF" OR "MXene" OR "graphene"))

The search covered publications from 2005 to 2025, enabling the analysis of two decades of research development. The search was limited to English-language publications to ensure consistency in bibliometric analysis and avoid potential translation ambiguities. Document types such as research articles, review articles, proceeding papers and early access records published in peer-reviewed journals were included. Furthermore, the search also was refined by Citation Topics Micro that selected only 11 topics including fuel cell membranes, polyoxometalates, electrospinning, metal-organic frameworks, layered double hydroxides, carbon nanotubes, ferroelectric crystals, mesoporous silica, boron nitride nano-materials, graphene and lastly, fullerene chemistry. Duplicate records and publications unrelated to SPEEK functionalization for proton exchange membrane applications were further removed through manual screening of titles and abstracts. The final dataset consisted of 513 publications, which formed the basis for all subsequent bibliometric analyses.

Bibliometric Analysis

The bibliometric analysis was conducted using the Bibliometrix package (version 4.4.1) in the R statistical environment, together with its web-based graphical interface, Biblioshiny [16, 17]. Bibliometrix is an open-source bibliometric toolkit that enables comprehensive science mapping, performance analysis, and visualization of bibliographic datasets. Biblioshiny provides an interactive platform that facilitates data pre-processing, statistical analysis, network construction, and graphical visualization without requiring advanced programming expertise. The bibliographic records exported from WoSCC in bibtex format were imported directly into Bibliometrix for data cleaning, standardization, and analysis.

The analysis comprised both performance analysis and science mapping to provide a comprehensive overview of the research field. Performance analysis was used to evaluate scientific productivity through annual publication trends, the most relevant publication sources, leading authors, productive institutions, and country-level scientific contributions. Annual scientific production was analysed to examine the temporal evolution of publications and identify growth patterns over the study period. Source analysis was performed to determine the journals contributing most significantly to the dissemination of SPEEK functionalization research. Author productivity and institutional analysis were conducted to identify the most influential researchers and leading research organizations, while country analysis revealed the global distribution of scientific output and research activities.

Science mapping techniques were subsequently employed to investigate the conceptual structure of the research field [18]. Keyword frequency analysis was performed to identify the most frequently occurring research topics, whereas keyword co-occurrence analysis was used to reveal relationships among research themes and visualize the knowledge structure through network mapping.

The bibliometric results were interpreted using descriptive statistical analysis and graphical visualizations generated by Biblioshiny. The combination of performance indicators and science mapping techniques enabled a comprehensive evaluation of publication trends, scientific productivity, collaboration patterns, conceptual evolution, and emerging research directions, thereby providing a holistic understanding of the global research landscape of emerging functionalization in SPEEK-based proton exchange membranes.

RESULTS AND DISCUSSION

General Characteristics of the Bibliometric Dataset

The bibliometric dataset was obtained from the main information as shown in Figure 1. The dataset comprised of 513 publications published between 2005 and 2025, providing a comprehensive overview of global research on emerging functionalization of SPEEK as proton exchange membranes for fuel cell applications. Though during the search, the publications was set from 2005 until 2025 but there were several studies in 2026 are included as dataset. These publications involved 1,601 authors, reflecting the multidisciplinary nature of the field, which integrates polymer chemistry, materials science, electrochemistry, and chemical engineering. The average of 5.75 co-authors per document indicate a strong collaborative research culture, highlighting the increasing importance of interdisciplinary expertise in developing advanced membrane materials. Furthermore, the relatively low proportion of single-authored publications suggests that research in this area is predominantly conducted through collaborative efforts involving multiple institutions and research groups.

Figure 1. Main information.

The dataset also demonstrates a broad international research participation, encompassing contributions from numerous institutions and countries, which underscores the global significance of proton exchange membrane research in supporting the transition toward sustainable energy technologies. The increasing involvement of international researchers reflects the growing scientific interest in developing cost-effective and high-performance alternatives to conventional PFSA membranes. Such collaborative activities facilitate knowledge exchange, accelerate technological innovation, and promote the development of multifunctional membrane materials with improved electrochemical performance and long-term durability.

Citation metrics further indicate the scientific influence of the retrieved publications. The dataset accumulated a substantial number of citations, with an average of 38.43 citations per document and 5.84 citations per document per year, suggesting that studies on SPEEK functionalization have received considerable attention within the fuel cell and polymer science communities. These citation levels imply that the field has generated influential contributions that continue to serve as important references for subsequent research. Collectively, the bibliometric indicators presented in Figure 1 reveal that research on SPEEK functionalization has evolved into a mature and internationally collaborative research domain characterized by sustained scientific productivity, high research impact, and increasing interdisciplinary participation, thereby providing a solid foundation for further exploration of publication trends, leading contributors, and emerging research themes.

Annual Scientific Production

The annual scientific production of publications related to emerging functionalization of SPEEK) exhibited a clear upward trajectory between 2005 and 2025, reflecting the growing research interest in advanced proton exchange membrane materials (Figure 2). During the initial stage (2005–2010), publication output remained relatively low, indicating that research was primarily focused on the fundamental development and characterization of SPEEK membranes. As the limitations of conventional PFSA membranes became increasingly recognized, research efforts gradually shifted toward improving the physicochemical properties of SPEEK through various functionalization strategies.

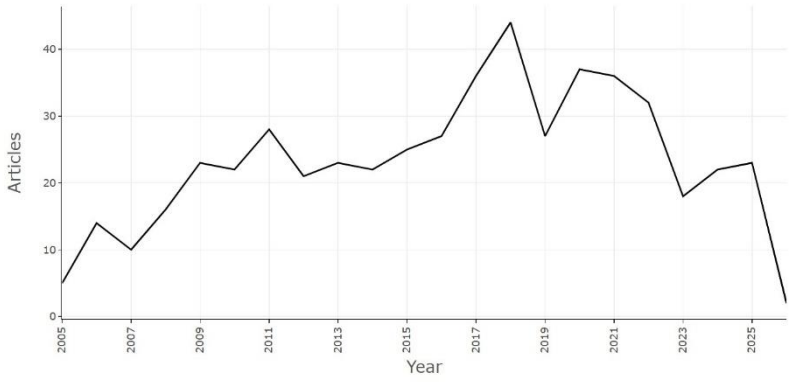

Figure 2. Publication production form 2005 until 2025.

Significant increase in publication output was observed during the subsequent decade, with the most significant growth occurring after 2015. This period coincided with rapid advances in nanomaterials, hybrid membrane fabrication, and membrane durability enhancement, which expanded the scope of SPEEK research and attracted greater scientific attention. The publication trend reached its highest level in the late 2010s to early 2020s, demonstrating that SPEEK functionalization had become an established and active research area within fuel cell technology.

Although slight year-to-year fluctuations were observed in the most recent years, the overall publication trend remained consistently high, indicating sustained scientific interest rather than a decline in research activity. Such fluctuations are common in bibliometric datasets and may reflect publication indexing timelines, funding cycles, or shifts toward emerging membrane technologies. Overall, the continuous increase in annual scientific production highlights the maturation of the research field and underscores the growing importance of SPEEK functionalization in addressing the performance and durability challenges of next-generation proton exchange membranes.

Source Analysis

The distribution of publications across scientific journals demonstrates that research on emerging functionalization of SPEEK is concentrated within a relatively small number of specialized, high-impact journals (Figure 3). This publication pattern reflects the interdisciplinary nature of the field, encompassing membrane science, polymer engineering, electrochemistry, and energy materials. The dominance of a limited number of core journals also indicates that these outlets serve as the primary platforms for disseminating advances in proton exchange membrane research.

Among the publication sources, the International Journal of Hydrogen Energy emerged as the most productive journal, highlighting its leading role in publishing fundamental and applied research on membrane materials and transport phenomena. Other highly productive journals, including the Journal of Membrane Science, the Journal of Power Sources, and the International Journal of Applied Polymer Science, further demonstrate the close relationship between membrane material development, fuel cell performance, and advanced polymer technologies. The prominence of these journals indicates that research on SPEEK functionalization is increasingly driven by the need to improve membrane durability, proton conductivity, and electrochemical performance for practical fuel cell applications.

The concentration of publications within a relatively small group of specialized journals suggests a well-established research community with clearly defined publication channels. This pattern also reflects the maturity of the field, where high-quality studies are consistently disseminated through internationally recognized journals with strong visibility and impact. Consequently, these journals not only shape the scientific direction of SPEEK functionalization research but also facilitate the exchange of knowledge among researchers working in membrane science, materials engineering, and sustainable energy technologies.

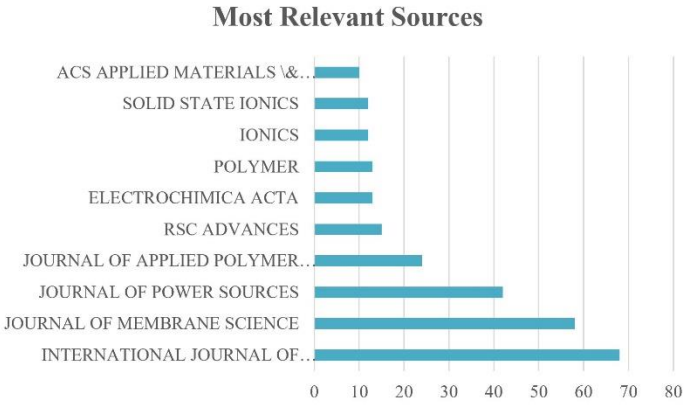

Figure 3. Most relevant sources.

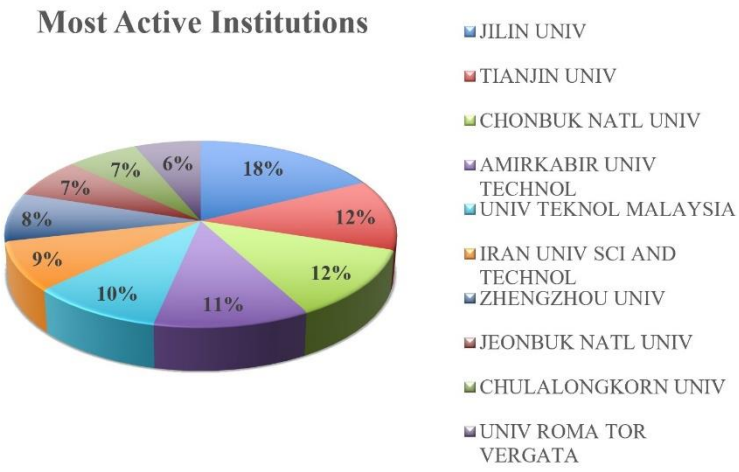

Figure 4. Top 10 active authors in the field.

Author and Institutional Productivity

Most Productive Authors

The analysis of author productivity reveals that research on SPEEK functionalization is driven by a relatively small group of highly productive researchers who have made sustained contributions to the development of advanced proton exchange membranes (Figure 4). These leading authors have significantly influenced the field through continuous publication of studies on membrane synthesis, functionalization strategies, nanocomposite design, and fuel cell performance. Their consistent research output has contributed to the establishment of a strong knowledge base, while collaborative authorship patterns indicate that scientific progress in this field is largely achieved through interdisciplinary and multi-institutional partnerships. Such collaborations facilitate the exchange of expertise across polymer science, electrochemistry, and materials engineering, thereby accelerating innovation in membrane development.

Leading Institutions

Institutional analysis shows that the most productive organizations are predominantly research-intensive universities and institutes with well-established expertise in membrane science, polymer materials, and fuel cell technologies (Figure 5). The concentration of publications within these institutions highlights their important role as global research hubs, supported by strong research infrastructure, sustained funding, and active international collaborations. The geographic distribution of leading institutions further indicates that research activity is concentrated in countries with significant investments in hydrogen and clean energy technologies. The presence of multiple productive institutions within the same regions also reflects the development of collaborative research networks that promote scientific excellence and facilitate the translation of fundamental membrane research into practical fuel cell applications. Overall, the productivity of leading authors and institutions underscores the collaborative and interdisciplinary nature of SPEEK functionalization research, which continues to drive innovation in proton exchange membrane materials.

Figure 5. Top 10 active authors in the field.

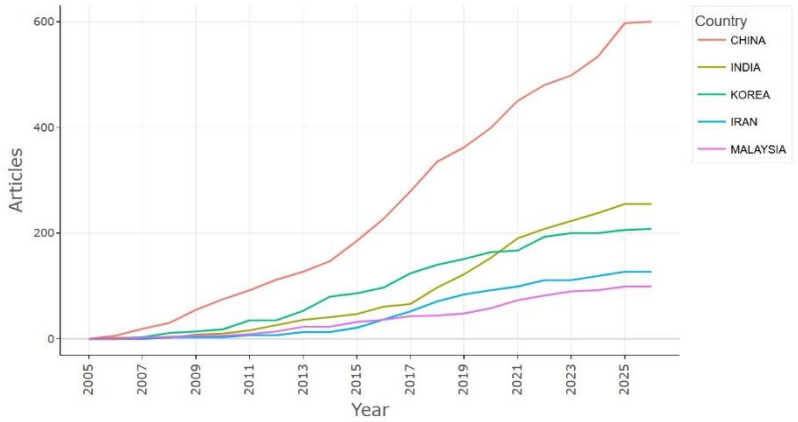

Figure 6. Number of articles produced by countries from 2005-2025.

Country Analysis

Scientific Production by Country

The country analysis indicates that research on emerging functionalization of SPEEK is dominated by a limited number of countries with strong research capabilities in fuel cells, advanced materials, and sustainable energy technologies (Figure 6). Among these, **China** emerged as the leading contributor, reflecting its substantial investment in hydrogen energy, membrane technology, and clean energy research. Other major contributors include **India, Korea, Iran** and **Malaysia**, highlighting the global interest in developing high-performance proton exchange membranes. The concentration of publications in these countries demonstrates their strong research infrastructure, active scientific communities and long-term commitment to advancing fuel cell technologies.

Global Research Distribution

The global distribution map further illustrates that research activities are concentrated primarily in **Asia, North America, and Europe**, with comparatively fewer contributions from Africa and South America (Figure 7). This uneven distribution suggests that scientific productivity is closely associated with national research funding, technological capacity, and the strategic importance of hydrogen energy within regional energy policies. The collaboration network also indicates increasing international partnerships among leading research nations, facilitating knowledge exchange and accelerating innovation in membrane materials. Expanding collaborations between established research hubs and emerging scientific communities could further enhance global research capacity, promote technology transfer, and support the development of next-generation proton exchange membranes for sustainable fuel cell applications.

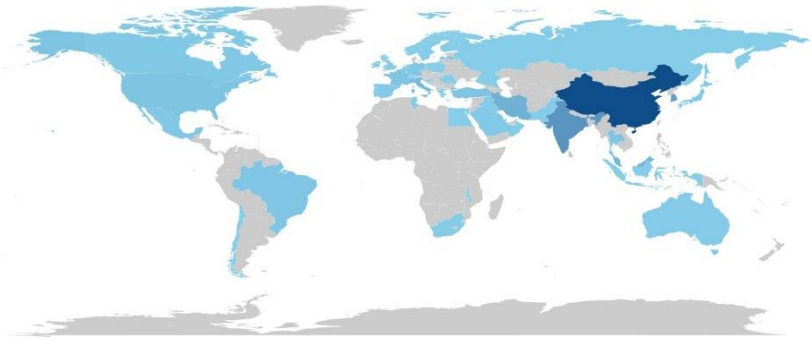

Figure 7. Map of active countries produced articles on the study.

Figure 8. Word cloud based on all keywords.

Research Hotspots

Keywords Frequency Analysis

The keyword frequency analysis provides an overview of the dominant research themes within the field of SPEEK functionalization (Figure 8). As expected, high-frequency keywords such as composite membranes, poly (ether ether ketone), membranes, performance, conductivity and proton exchange membrane represent the core focus of the research area. The frequent occurrence of terms related to polymer electrolyte membranes; nanocomposites membranes and graphene oxide indicate a growing emphasis on enhancing membrane performance through advanced material modification. These keyword trends suggest that recent research has shifted beyond conventional membrane fabrication towards the development of multifunctional membranes with improved conductivity, durability, and mechanical stability.

Keywords Co-occurrence Network

The keyword co-occurrence network further reveals the conceptual structure of the research field by grouping related keywords into interconnected thematic clusters (Figure 9). The largest cluster is centred on composite membrane, representing the fundamental research on membrane modification and electrochemical performance. Other clusters are associated with functionalization strategies, including carbon-based materials such as graphene oxide highlighting the multidisciplinary nature of the field. The strong interconnections among these clusters demonstrate that current research increasingly integrates material design, membrane engineering, and fuel cell performance evaluation rather than addressing these aspects independently. Overall, the keyword network indicates that improving proton conductivity, reducing fuel crossover, and enhancing long-term membrane stability remain the principal research priorities, while advanced functionalization approaches continue to shape the future direction of SPEEK-based proton exchange membrane research.

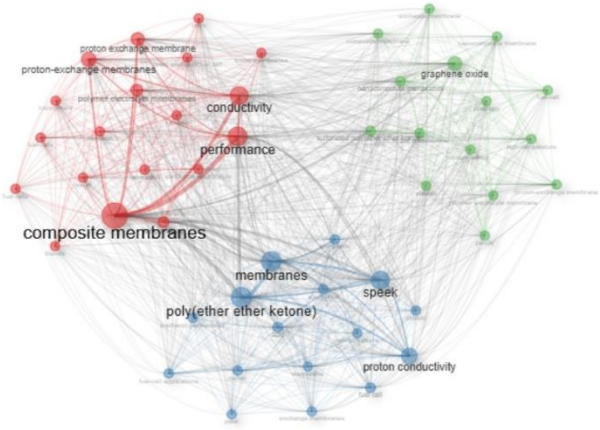

Figure 9. Co-occurrence network based on all keywords.

Research Trends and Future Perspectives

Current research trends in SPEEK-based proton exchange membranes are strongly oriented toward multifunctional material design, nanoscale engineering, and durability enhancement under real fuel cell conditions. A dominant direction is the development of hybrid and nanocomposite membranes that integrate functional fillers to simultaneously improve proton conductivity, mechanical stability, and oxidative resistance. Advanced materials such as graphene-based structures, metal–organic frameworks, and functionalized nanoparticles are increasingly explored to create well-defined proton transport channels and improve the performance of fuel cell systems.

Another important trend is the focus on long-term membrane stability and degradation resistance. Research is increasingly addressing oxidative degradation mechanisms, radical scavenging strategies and structural reinforcement approaches to extend membrane lifespan under harsh electrochemical environments. In parallel, there is growing interest in green and sustainable fabrication routes, including environmentally friendly sulfonation processes and bio-derived or low-toxicity additives.

Looking forward, future research is expected to move toward rational molecular-level design of SPEEK-based membranes, supported by computational modelling and advanced in-situ characterization techniques. Integration of artificial intelligence and machine learning for materials optimization is also anticipated to accelerate discovery of high-performance membrane systems. Furthermore, scaling up fabrication methods and improving cost-effectiveness will be essential for commercial deployment. Overall, the future of SPEEK functionalization research lies in the convergence of materials innovation, mechanistic understanding, and practical fuel cell integration, enabling next-generation proton exchange membranes with superior efficiency and durability.

CONCLUSION

This study presents a comprehensive bibliometric analysis of global research on emerging functionalization of (SPEEK) as proton exchange membranes for fuel cell applications over the period 2005–2025. By utilizing the WoSCC and applying Bibliometrix and Biblioshiny tools, the study systematically mapped publication trends, citation impact, collaborative structures, and thematic evolution within this rapidly expanding research field. A total of 513 publications were analyzed, revealing sustained scientific growth and increasing interdisciplinary integration across polymer science, materials engineering, and electrochemistry.

The performance analysis demonstrates that SPEEK functionalization research has evolved into a mature and globally distributed field characterized by high collaboration intensity and consistent citation impact. Annual scientific production shows a strong upward trajectory, particularly after 2015, reflecting accelerated interest in nanocomposite membrane development and fuel cell performance enhancement. Journal analysis indicates that research output is concentrated in a small number of high-impact journals, particularly those focused on energy, membrane science, and polymer technology, highlighting well-established dissemination channels within the field.

Author, institutional, and country-level analyses reveal that research activity is driven by a combination of highly productive researchers and leading institutions, predominantly located in Asia, Europe, and North America. China emerges as the most influential contributor, followed by other active countries such as India, Korea, Iran, and Malaysia.

These findings highlight the importance of national research investment and international collaboration in advancing proton exchange membrane technologies.

The science mapping results further reveal that the intellectual structure of the field is centered on composite membranes, proton conductivity enhancement, and nanomaterial-based functionalization strategies. Keyword co-occurrence analysis indicates a clear shift from conventional SPEEK membrane development toward advanced multifunctional systems incorporating graphene derivatives, metal–organic frameworks, and hybrid nanostructures. This evolution reflects the growing emphasis on simultaneously improving membrane conductivity, durability, and resistance to methanol crossover and oxidative degradation.

Overall, the thematic evolution and research trend analysis demonstrate that SPEEK functionalization research is transitioning from material optimization toward rational, multifunctional, and performance-driven membrane design. Emerging directions emphasize nanostructured hybrid systems, degradation-resistant architectures, green synthesis approaches, and data-driven material discovery using computational modelling and artificial intelligence.

In conclusion, this bibliometric study provides a systematic and quantitative overview of the development, structure, and future trajectory of SPEEK-based proton exchange membrane research. The findings not only highlight the maturity and interdisciplinary nature of the field but also identify key research gaps and emerging opportunities. Future progress is expected to depend on the integration of advanced material engineering, mechanistic understanding of degradation processes, and scalable fabrication strategies to enable the commercialization of high-performance, durable, and cost-effective proton exchange membranes for next-generation fuel cell technologies.

ACKNOWLEDGEMENTS

The authors acknowledge Universiti Teknologi Malaysia (UTM) for financial support and research facilities.

REFERENCES

1. Okamoto, N., Wang, F. and Watanabe, T. (2014) Adhesion of electrodeposited copper, nickel, and silver films on copper, nickel, and silver substrates. *Materials Transaction*, **45**, 3330–3333.

2. Wang, L., Hu, C. and Shoa, L. (2017) The antimicrobial activity of nanoparticles: present situation and prospects for the future. *International Journal of Nanomedicine*, **12**, 1227–1249.

3. Zhao, A. P., Li, S., Xie, D., Wang, Y., Li, Z., Hu, P. J. -H. and Zhang, Q. (2025) Hydrogen as the nexus of future sustainable transport and energy systems. *Nature Reviews Electrical Engineering*, **2(7)**, 447–466.

4. Wang, Z., Liu, Z., Fan, L., Du, Q. and Jiao, K. (2023) Application progress of small-scale proton exchange membrane fuel cell. *Energy Reviews*, **2(2)**, 100017.

5. Haider, R., Wen, Y., Ma, Z. F., Wilkinson, D. P., Zhang, L., Yuan, X. and Zhang, J. (2021) High temperature proton exchange membrane fuel cells: Progress in advanced materials and key technologies. *Chemical Society Reviews*, **50(2)**, 1138–1187.

6. Maiti, T. K., Singh, J., Dixit, P., Majhi, J., Bhushan, S., Bandyopadhyay, A. and Chattopadhyay, S. (2022) Advances in perfluorosulfonic acid-based proton exchange membranes for fuel cell applications: A review. *Chemical Engineering Journal Advances*, **12**, 100372.

7. Kassa, T. S., Yessuf, A. M., Mohideen, M. M., Mihiretu, A. M., Ramakrishna, S. and Liu, Y. (2025) Modification, degradation, and mitigation of perfluorosulfonic acid proton exchange membranes for fuel cells: A review. *ACS Applied Materials & Interfaces*, **17(32)**, 45271–45301.

8. Tamer, M., Akyalçın, S. and Akyalçın, L. (2024) Recent progresses and challenges to determine properties of sulfonated polyether ether ketone based electrolytes for direct methanol fuel cell applications. *ChemElectroChem*., **11(23)**, 1-36

9. Jaafar, J., Ismail, A. F., Matsuura, T. and Nagai, K. (2011) Performance of SPEEK based polymer-nanoclay inorganic membrane for DMFC. *Journal of Membrane Science*, **382(1–2)**, 202–211.

10. Iulianelli, A. and Basile, A. (2012) Sulfonated PEEK-based polymers in PEMFC and DMFC applications: A review. *International Journal of Hydrogen Energy*, **37(20)**, 15241–15255.

11. Segale, M., Seadira, T., Sigwadi, R., Mokrani, T. and Summers, G. (2024) A new frontier towards the development of efficient SPEEK polymer membranes for PEM fuel cell applications: A review. *Materials Advances*.

12. Jaafar, J., Ismail, A.F. and Matsuura, T. (2009) Preparation and barrier properties of SPEEK/ Cloisite 15A®/TAP nanocomposite membrane for DMFC application. *Journal of Membrane Science*, **345(1–2)**, 119–127.

13. Kamal, M., Jaafar, J., Khan, A. A., Khan, Z., Ismail, A. F., Othman, M. H. D. and Rehman, G.

U. (2024) A critical review of the advancement approach and strategy in SPEEK-based polymer electrolyte membrane for hydrogen fuel cell application. *Energy & Fuels*, **38(14)**, 12337–12386.

14. Wang, Q. (2018) Distribution features and intellectual structures of digital humanities: A bibliometric analysis. *Journal of Documentation*, **74(1)**, 223–246.

15. Cindrella, L., Fu, H. Z. and Ho, Y. S. (2014) Global thrust on fuel cells and their sustainability – an assessment of research trends by bibliometric analysis. *International Journal of Sustainable Energy*, **33(1),** 125–140.

16. Magama, N., Ojemaye, M. O., Manene, N. C., Okoh, O. O. and Okoh, A. I. (2024) Global research progression on electro-catalysts for direct methanol fuel cells between 1992 and 2023 using bibliometric indicators. *Ionics*, **30(10)**, 5951–5968.

17. Khoiruddin, K., Nandar, C. S. A., Kawi, S., Lim, T. M. and Wenten, I. G. (2025) Advanced proton exchange membranes for high-efficiency fuel cells: Material innovations and durability optimization. *Energy Materials*, **5(11)**.

18. Aria, M., Cuccurullo, C., D'Aniello, L. and Spano, M. (2026) Biblioshiny and the SAAS workflow: An integrated framework for transparent and reproducible science mapping. A demonstration through the replication of a study. *Journal of Informetrics*, **20(3)**, 101837.

19. Aria, M. and Cuccurullo, C. (2017) Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, **11(4)**, 959–975.

20. Aria, M., Cuccurullo, C., D'Aniello, L., Misuraca, M. and Spano, M. (2024) Comparative science mapping: A novel conceptual structure analysis with metadata. *Scientometrics*, **129(11)**, 7055–7081.