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Trends In PVDF-HFP Polymer Electrolytes Use In Electrochemical Device Energy Storage: A Bibliometric Analysis

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ABSTRACT

This study presents a bibliometric analysis of research trends on PVDF-HFP polymer electrolytes for electrochemical energy storage applications. Data were retrieved from two major scientific databases, Scopus and Web of Science, covering publications from 2015 to 2025. The analysis examines the evolution of research over the past decade, with a focus on synthesis strategies, development of PVDF-HFP-based polymer electrolytes, leading contributing countries, annual publication trends, and comparative insights between both databases. VOSviewer software was employed to visualize keyword co-occurrence networks and identify dominant research themes associated with PVDF-HFP systems. The findings reveal a consistent growth in scientific output, with more than 12 relevant publications identified, and indicate that "gel polymer electrolyte" is the most frequently occurring keyword across both datasets. Overall, this study provides a structured overview of the research landscape and highlights emerging directions in PVDF-HFP polymer electrolyte research.

INTRODUCTION

Notable advancements in energy storage devices have led to increasing research into improved materials for electrochemical applications, especially polymer electrolytes (Ramaiah et al., 2021). Typically, research in polymer electrolytes aims to develop materials with enhanced ionic conductivity and mechanical stability, addressing key limitations of liquid electrolytes in devices like lithium-polymer batteries (Ismail et al., 2025). The amorphous nature of hexafluoropropylene (HFP), which enhances ion mobility, and the crystalline regions of polyvinylidene fluoride (PVDF), which provide mechanical strength, are two characteristics of poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) among

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the different polymer electrolytes (Ahmad et al., 2018). As a result, this situation makes PVDF-HFP an excellent candidate for polymer electrolyte membranes. Furthermore, PVDF-HFP is effective because it processes at a lower temperature, bends easily, and resists electrical polarisation due to its low dielectric response (Ruandroew et al., 2022). Researchers often rely on PVDF-HFP because it resists electrochemical breakdowns while strongly interacting with liquid electrolytes (Jakriya et al., 2018). The growing number of research in this area poses challenges in analysing the extensive and rapidly advancing academic publications, thus requiring a systematic bibliometric analysis to identify current trends, key research clusters, and future research trajectories. Bibliometric studies are used by researchers, organisations, and politicians to assess efficiency, detect new trends, and decide on research funding and collaborations (Hassan & Duarte, 2024). Moreover, this analysis assists researchers in comprehending journal performance for the selection of the most suitable publication areas, therefore developing technological advancement and enhancing researcher's reputation (Surekha et al., 2024).

In this context, bibliometric analysis serves as a robust quantitative methodology for assessing the academic landscape and identifying emerging trends within specific research domains (Agyekum et al., 2022). Bibliometric studies systematically analyse publication data, including citation patterns, co-authorship networks, and keyword occurrences, to map the intellectual structure and evolution of a field, such as the use of PVDF-HFP polymer electrolytes in electrochemical energy storage (El-Masry, 2023). Through this technique, scholars work with publication records, apply indicators, and create visualisations to trace patterns and highlight emerging directions in the field (Yousef et al., 2023). This approach provides a basic understanding and literature evaluation for certain fields (Hananda et al., 2023). By identifying influential studies, research hotspots, and temporal trends, this method not only summarises the existing knowledge landscape but also forecasts future research directions within the domain of PVDF-HFP polymer electrolytes (Xiong et al., 2022). This analytical approach facilitates a comprehensive understanding of publication patterns, key contributors, influential works, and thematic shifts in the field of PVDF-HFP polymer electrolytes for electrochemical energy storage (Chen et al., 2023). Research on PVDF-HFP polymer electrolytes has reached a stage where a bibliometric study can clarify how the field has progressed. For example, a bibliometric review on ionic liquid electrolytes for energy storage has tracked 2,486 papers, published between 2019 to 2024 in Web of Science and Scopus, revealed rapid growth and several notable advances (Kaur et al., 2025). To achieve this, researchers often rely on software such as VOSviewer, CiteSpace, and Bibliometrix, which help map citation activity, monitor evolving themes, and illustrate networks of collaboration.

VOSviewer is very effective for displaying large maps, facilitating understanding, and is mostly utilized in the generation of maps derived from network data (Gu et al., 2021). This software enables the identification of highly cited papers, prominent authors, and leading institutions, thus assessing the quality and amount of published research (Zahoor et al., 2024). In VOSviewer, keyword occurrence and co-occurrence techniques are commonly employed to delineate thematic clusters and pinpoint emerging research frontiers within a given scientific field (Purwanto et al., 2024). These co-occurrence patterns are essential for outlining the intellectual framework of the research subject, revealing commonly studied topics and their connections (Ng, 2025). Additionally, VOSviewer categorises similar keywords into clusters that signify specific research trends within this field of study. In the visualisation map, each node signifies an entity, such as a keyword or author, with its size reflecting its frequency or influence within the network, while the connections between nodes denote their co-occurrence associations (Chen et al., 2023). The insights derived using VOSviewer could clarify the relationships among various terms, demonstrate the frequency of their co-occurrence, and map the development of research fronts in the domain of PVDF-HFP polymer electrolytes (Palmas et al., 2023).

A bibliometric analysis of PVDF-HFP polymer electrolytes employed in electrochemical devices provides a comprehensive overview of research progression and the intellectual structure of the field. In parallel, a recent bibliometric study on PVDF has been reported, highlighting its diverse applications in the

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medical and pharmaceutical sectors (Concha et al., 2024), thereby underscoring the material's broad scientific and technological relevance across disciplines. However, despite its prominence as a widely investigated and rapidly emerging polymer, systematic bibliometric evaluations focusing specifically on PVDF-HFP as a polymer electrolyte remain notably scarce within the Scopus and Web of Science databases. To address this gap, the present study delivers a comprehensive bibliometric interrogation of PVDF-HFP-based polymer electrolytes in electrochemical systems, with particular emphasis on electrolyte classifications, salt chemistries, and energy storage architectures. Leveraging datasets spanning 2015–2025, this work maps the evolution of knowledge production, intellectual structure, and research dynamics within the field. In addition, recent advances in synthesis strategies and material design are critically examined to elucidate prevailing patterns, uncover emerging research frontiers, and establish a forward-looking perspective that informs the rational development of next-generation PVDF-HFP polymer electrolyte systems, specifically.

METHODOLOGY

This study investigates the application of PVDF-HFP polymer electrolytes in electrochemical devices for energy storage purposes and employs a bibliometric analysis to systematically evaluate the research landscape. The review was conducted through three main stages: data collection, data processing, and bibliometric analysis, ensuring a structured and rigorous approach to mapping research trends and developments in the field.

Data Collection

Data collection was conducted through two primary stages: data acquisition, and filtering. Relevant publications were retrieved using the keywords "PVDF-HFP", "polymer electrolyte", "energy storage", and "electrochemical devices", with the search limited to the publication period of 2015 to 2025 across both the Web of Science and Scopus databases.

Data Processing

For the Scopus database, all records were exported in CSV format, including citation information, abstracts, and keywords, to facilitate comprehensive analysis and systematic preprocessing. For the Web of Science database, records were exported as tab-delimited files including full records and cited references.

Data Cleaning

The dataset was subsequently imported into Microsoft Excel for data cleaning. Duplicate entries were systematically identified through cross-comparison of titles, author names, and publication years, and only a single, complete record was retained for each publication to ensure data integrity and analytical accuracy.

Bibliometric Analysis

After the data cleaning process, the refined dataset was imported into VOSviewer (version 1.6.20), a widely used software tool for constructing and visualizing bibliometric networks. VOSviewer applies clustering techniques to map relationships such as co-authorship, co-citation, and keyword co-occurrence, enabling the identification of underlying research structures. In VOSviewer, nodes represent keywords, while link strength indicates relationship between research topics. In this study, it was employed to generate term co-occurrence visualisations, facilitating the identification of major research themes and their interconnections within the PVDF-HFP polymer electrolyte domain.

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To construct the co-occurrence map, several parameters were carefully defined. The data type was set to bibliographic data, with the source specified as bibliographic database files. Records retrieved from both the Web of Science (WoS) and Scopus databases were used as input. The analysis type was selected as co-occurrence, with keywords designated as the unit of analysis, and full counting was applied to ensure comprehensive representation of term frequencies. A minimum occurrence threshold was established to filter and include only relevant terms in the network visualisation.

A comprehensive thematic overview was achieved by initially considering all available keywords, ensuring the widest possible range of research terminology was captured. Prior to final network generation, selected keywords were manually validated to ensure accuracy and consistency. Finally, results from both databases were integrated and compared, enabling a more robust and holistic representation of current research trends and developments in the field.

RESULT AND DISCUSSION

Research Trends

In the past decades, various synthesis methods such as solution casting, electrospinning and others have been used to prepare PVDF-HFP-based polymer electrolytes. Each of these methods produces different electrochemical characteristics and performance results. Table 1 summarizes these methods, including their ionic conductivities and applications in electrochemical devices.

Table 1. Synthesis methods for PVDF-HFP polymer electrolyte

Synthesis method	Ionic conductivity (σ)	Application	Cited study
Solution casting	7.24×10^{-4} Scm^{-1}	Li metal polymer battery	Jie et al., 2020
Electrospinning	2.34×10^{-3} Scm^{-1}	Lithium metal batteries	Gan et al., 2021
Phase inversion	0.71×10^{-3} Scm^{-1}	Sodium-ion batteries	Das et al., 2023
Hot pressing	2.12×10^{-4} Scm^{-1}	Lithium batteries	Shokrieh et al., 2024
In-situ polymerization	1.01×10^{-3} Scm^{-1}	Solid lithium metal batteries	Yuan et al., 2025
Sol-gel method	2.83×10^{-3} Scm^{-1}	Sodium-ion batteries	Wang et al., 2021

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The most common method is solution casting. PVDF-HFP can be easily formed into thin film using these methods, where the polymers are dissolved in solvents like acetone, DMF, or NMP. A study done by Jie et al. shows when combined with LiTFSI and DMF, this method produces lithium metal batteries with good ionic conductivity of 7.24×10^{-4} Scm^{-1} at 70°C (Jie et al., 2020). Besides that, from Gan et al. research, electrospinning is another technique that uses high voltage to create fibrous membranes with strong mechanical properties, high electrolyte absorption, and good thermal conductivity. With combinations of $LiPF_6$ and NMP, it can reach conductivity levels of 2.34×10^{-3} Scm^{-1} (Gan et al., 2021).

Furthermore, phase inversion technique works differently as this method involves placing the polymer solution into a non-solvent bath to trigger phase separation. Using this method produces membranes that are stable and resistant to shrinking that are suitable for sodium-ion batteries. In this technique, Das et al. use DMAc-acetone, SiO_2, and $NaClO_4$ and the resulting ionic conductivity achieved 0.71×10^{-3} Scm^{-1} (Das et al., 2023). On the other hand, hot pressing techniques are also used to synthesize polymer electrolyte. This technique uses heat and pressure to shape polymer blends. In lithium batteries, adding LiTFSI and MDF helps to improve bonding and structure, this proven by the resulting ionic conductivity achieved 2.12×10^{-4} Scm^{-1} (Shokrieh et al., 2024).

Additionally, in-situ polymerization procedures were applied by incorporating the monomers or salts directly into the PVDF-HFP before polymerization. This technique helps to improve contact and lower resistance. Yuan et al. used LiTFSI, DMF, acetone, and YSZ fillers to reach 1.01×10^{-3} Scm^{-1} conductivity at 30°C in solid-state lithium batteries (Yuan et., 2025). Lastly, the sol-gel method embeds inorganic fillers into the polymer matrix to increase porosity and reduce crystallinity, improving the liquid electrolyte absorption. DMF and EG with $Na_2Ze_xSiPO_{12}$ filler were used in sodium-ion batteries and the resulting ionic conductivity achieved 2.83×10^{-3} Scm^{-1} (Wang et al., 2021). In summary, based on the variance of synthesis techniques above proves the adaptability of PVDF-HFP as a versatile material across various energy storage applications.

Table 2 provides a past decade of studies of PVDF-HFP based polymer electrolytes across several journals. For instance, researchers have investigated the use of different salts, such as LiTFSI, $LiClO_4$, and $LiBF_4$, as well as incorporation of fillers, like TiO_2, SiO_2, and $BaWO_4$ into PVDF-HFP polymer electrolytes. These studies have identified techniques that offer enhancement of ionic conductivity and electrochemical stability through modification in salts, solvents and formulation process.

As research done by Song et al. (2015) studied TiO_2 nanoparticles that enhanced porosity and thermal characteristics of Li-ion battery electrolyte that achieve high conductivity results of 10^{-3} Scm^{-1}. On the other hand, Vekantesan et al. (2016) investigated the efficacy of TiC and TiO_2 nanofillers incorporated into gel electrolytes that are used for dye-sensitized solar cells with excellent conductivity of 10^{-3} Scm^{-1}. Next, a study done by Ubarhande et al. (2017) shows the influence of different content of silica in the polymer matrix for the purpose of improving the performance of separators in lithium-ion batteries. Meanwhile, the potential of electrospun nanohybrid polymer membranes for all solid-state lithium-ion capacitors have been demonstrated by Maurya et al. (2019) with 10^{-3} Scm^{-1} conductivity.

In addition, PVDF-HFP based electrolytes for carbon supercapacitors were studied by Bhat et al. (2020) who highlighted the enhancement of the electrolyte in their paper with achievement of 10^{-3} Scm^{-1} conductivity. In 2021, Shuttle-like $BaWO_4$ nanostructures were introduced by Paramanantham et al. to enhance the PVDF-HFP membranes' electrochemical and physical characteristics for direct methanol fuel cells. In contrast to electrodes created with traditional NBR in solid-state batteries, Kim et al. (2022) highlighted the density and dispersion of polymeric binders in improving the performance of electrodes made with PVDF-HFP.

As research advanced, Kumari et al. (2023) looked at gel polymer electrolytes based on glyme for high-voltage magnesium-ion batteries. Additionally, Wei et al. (2024) investigated the use of cellulose acetate into PVDF-HFP gel electrolytes to enhance mechanical properties and thermal stability for lithium-metal

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batteries. By combining a deep eutectic solvent (DES) made of MSM, $LiClO_4$, and water in a 1.8:1:1 molar ratio with a porous PVDF-HFP matrix, Huang et al. (2025) improved the ionic conductivity of supercapacitors.

Table 2. Development of PVDF-HFP based polymer electrolytes: Application and ionic conductivity (2015-2025)

Year	Journal	Authors	Materials	Ionic Conductivity	Application Area
2015	Solid State Ionics	Song et al	PVDF-HFP,PMMA **Filler:** TiO_2 **Solvent:** DMF	10^{-3}S·cm^{-1} at room temperature (China)	Lithium-Ion Batteries
2016	Journal of Power Sources	Venkatesan et al	PVDF-HFP, Propionitrile, 4-tert butylpyridine, DMPII **Filler:** TiO_2, TiC **Solvent:** Methoxypropionitrile	10^{-3}S·cm^{-1} at room temperature (Taiwan)	Dye-sensitized solar cells
2017	IOP Conference Series: Materials Science and Engineering	Ubarhande et al	PVDF-HFP, PEMA **Salts:** $LiClO_4$, $LiN(CF_3SO_2)_2$, $LiBF_4$, $LiCF_3SO_3$ **Solvent:** Acetone	10^{-3}S·cm^{-1} at temperature 303K, 318K, 333K, 353K, 373K	Lithium battery applications
2018	Nanomaterials	Caimi et al	PVDF-HFP, Sodium dodecyl sulphate, N-Propyl-N-Methylpyrrolidinium bis(trifluoromethane-sulfonyl)-imide, Solvionic **Salt:** LiTFSI **Filler:** SiO_2	10^{-3}S·cm^{-1} at room temperature (Switzerland)	Lithium-Ion Batteries
2019	The Journal of Physical Chemistry	Maurya et al	PVDF-HFP, $LiPF_6$, EC, DMC **Filler:** $Li_{7.1}La_3Ba_{0.05}Zr_{1.95}O_{12}$ **Solvent:** DMAc, Acetone	10^{-3}S·cm^{-1} at 25°C	Li-Ion capacitor
2020	Materials Science & Engineering B	Bhat et al	PVDF-HFP, Suberonitrile (SUN) **Salt:** LiTFSI	10^{-3}S·cm^{-1} at room temperature (India)	Supercapacitor
2021	Solid State Ionics	Paramanantham et al	PVDF-HFP, $BaCl_2$, $SrCl_2.6H_2O$, $Na_2WO_4.2H_2O$, CTAB, Urea, $ClSO_3H$ **Filler:** shuttle-like $BaWO_4$ **Solvent:** DMF, Ethanol	10^{-2}S·cm^{-1} at 80°C	Direct methanol fuel cells (DMFCs)
2022	Chemical Engineering Journal	Kim et al	PVDF-HFP, LPSX, LiCl, P_2S_5, Li_2S **Polymeric Binder:** NBR **Solvent:** EA, HB	10^{-3}S·cm^{-1} at room temperature (Korea)	Solid-state Batteries
2023	Applied Energy Materials	Kumari et al	PVDF-HFP, Diglyme (G2) **Salt:** $Mg(ClO_4)_2$ **Solvent:** Acetone and NMP	10^{-3}S·cm^{-1} at room temperature (～30°C)	Magnesium-Ion Batteries
2024	Chemical Engineering Journal	Wei et al	PVDF-HFP, Cellulose Acetate (CA) **Salt:** LiTFSI	10^{-3}S·cm^{-1} at room temperature (China)	Lithium metal Batteries
2025	Electrochimica Acta	Huang et al	PVDF-HFP, Methylsulfonylmethane, CMC, Activated carbon	10^{-3}S·cm^{-1} (not stated temperature)	Supercapacitors

Publication Trends

This bibliometric study examined emerging publication trends on PVDF-HFP polymer electrolytes in electrochemical energy storage systems, drawing data from the Scopus database. The search spanned publications from 2015 to 2025 and used keywords such as “PVDF-HFP”, “polymer”, “electrolytes”, “electrochemical device”, and “energy storage”. A total of 49 papers were retrieved, reflecting the growing academic interest in this field. To visualize the landscape, VOSviewer was employed to generate author

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collaboration networks and keyword co-occurrence maps, offering insight into the structural and thematic evolution of the research domain.

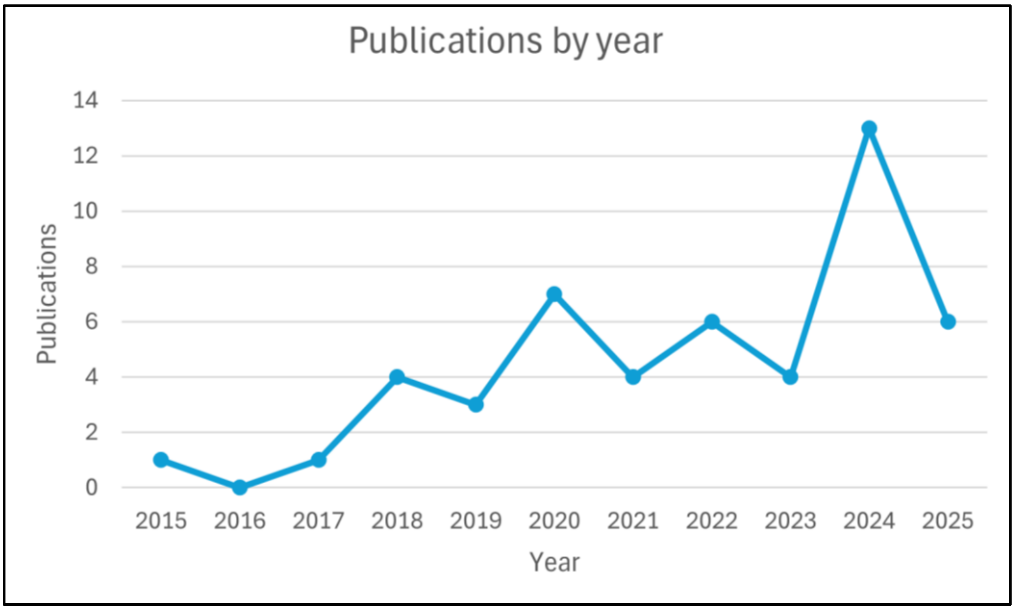

Fig. 1. Annual Research Output Recorded in Scopus from 2015 to 2025
Source: Data retrieved from Scopus

The trends of publications on PVDF-HFP polymer electrolytes for electrochemical energy storage from 2015 to 2025 is shown in figure 1. The research output, which began in 2015, shows an inconsistent but generally developing pattern after first decreasing to zero documents in 2016 and increasing with one publication in 2017. The number of papers increased to four in 2018, then decreased slightly to three in 2019, before increasing the following year to a peak of seven in 2020. After a brief reduction to four papers in 2021, the number of documents increased significantly to six documents in 2022 and decreased to four publications in 2023. A notable increase in publications in 2024, with a peak of 13 papers, indicated this topic has had rapid research and outstanding current interest. The significant decrease in 2025 to about six papers indicates that the data for that year may be unfinished given it is the current year and not all articles have likely been indexed so far.

Next, an analysis was conducted using the Web of Science (WoS) database, focusing on the keywords "PVDF-HFP", "polymer electrolyte", "electrochemical devices", and "energy storage". A total of 70 publications were identified, spanning the years 2015 to 2025. WoS provides a detailed overview of the collected data, including publication year, document type, author, subject area, country or region, and research field.

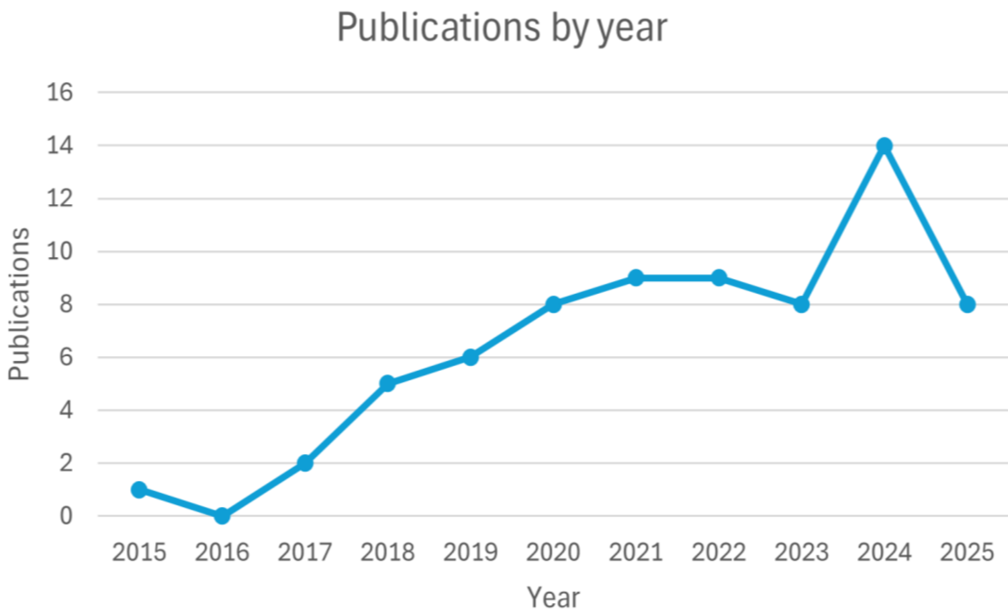

Fig 2. Annual research output recorded in WoS from 2015 to 2025
Source: Data retrieved from WoS

Figure 2 illustrates the number of research publications on PVDF-HFP polymer electrolytes recorded between 2015 and 2025. From the figure above, the data showed a steady increase in research interest. In 2024 marked the highest peak in publication output with 14 publications. This proved the growing interest of PVDF-HFP-based polymer electrolyte in that year. In contrast, the year 2016 recorded the fewest articles with no publication recorded followed by 2015 with one publication. Based on the overall data, a steady increase highlights the growing relevance of PVDF-HFP polymer electrolytes. This is due to researchers that continue to explore their potential to enhance electrochemical performance and support the development of energy storage in both science and engineering fields.

Geographic Distribution

The top ten global distribution of the research output on PVDF-HFP polymer electrolytes for electrochemical energy storage devices based on the scopus database is illustrated in Figure 3. It demonstrates clearly that China is the main contributor, leading significantly with 24 number of publications, followed by India in the second with about 16 documents. Hence, it shows that the research in PVDF-HFP is primarily centered in China. Additionally contributing nations include Taiwan (4 papers), Malaysia (3 documents), Poland (2 documents), South Korea (2 documents), and the United States (2 documents), each exhibiting a much-reduced number of publications. Thus, it emphasizes active research community and established infrastructure in East and Southeast Asian countries within this particular

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domain. Furthermore, this trend indicates the excellent research capabilities of these countries and their increasing in polymer research and its applications.

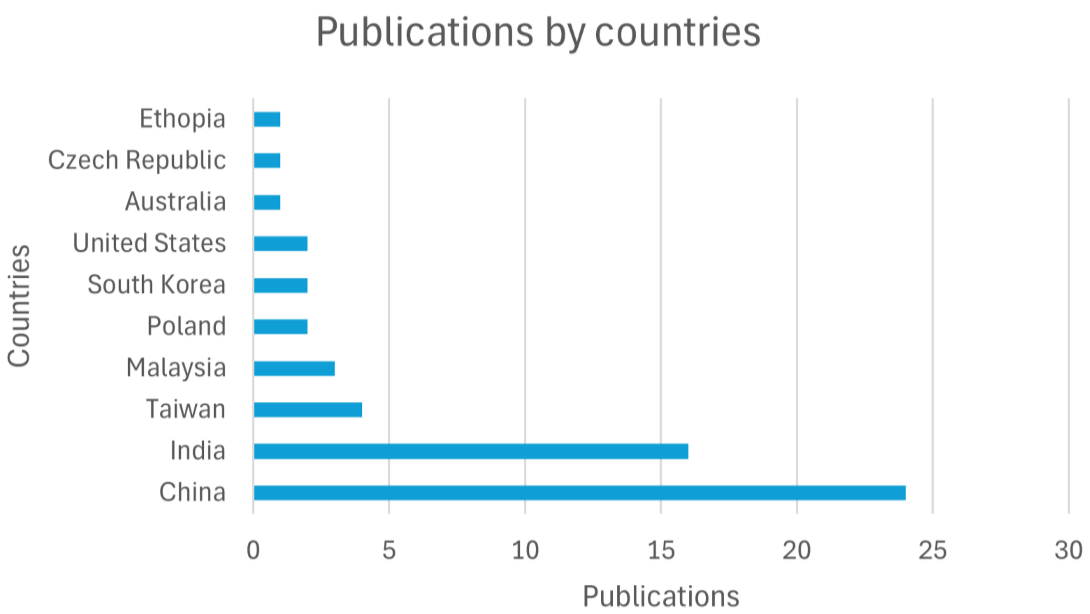

Fig. 3. Top contributing countries by Scopus Document Count
Source: Data retrieved from Scopus

Figure 4 presents data from the WoS database, highlighting the top ten countries contributing to PVDF-HFP polymer electrolyte research. From the figure above, the data showed People R China leads with 31 publications followed by India with 21 publications. Malaysia ranks third with 5 publications. Taiwan, South Korea, and the USA produced four publications each while Australia, Germany, Italy, and Poland each contributed two papers. This geographic distribution shows different levels of global research activity with China leads strongly, while other regions are steadily increasing their involvement in developing PVDF-HFP as polymer electrolytes technologies.

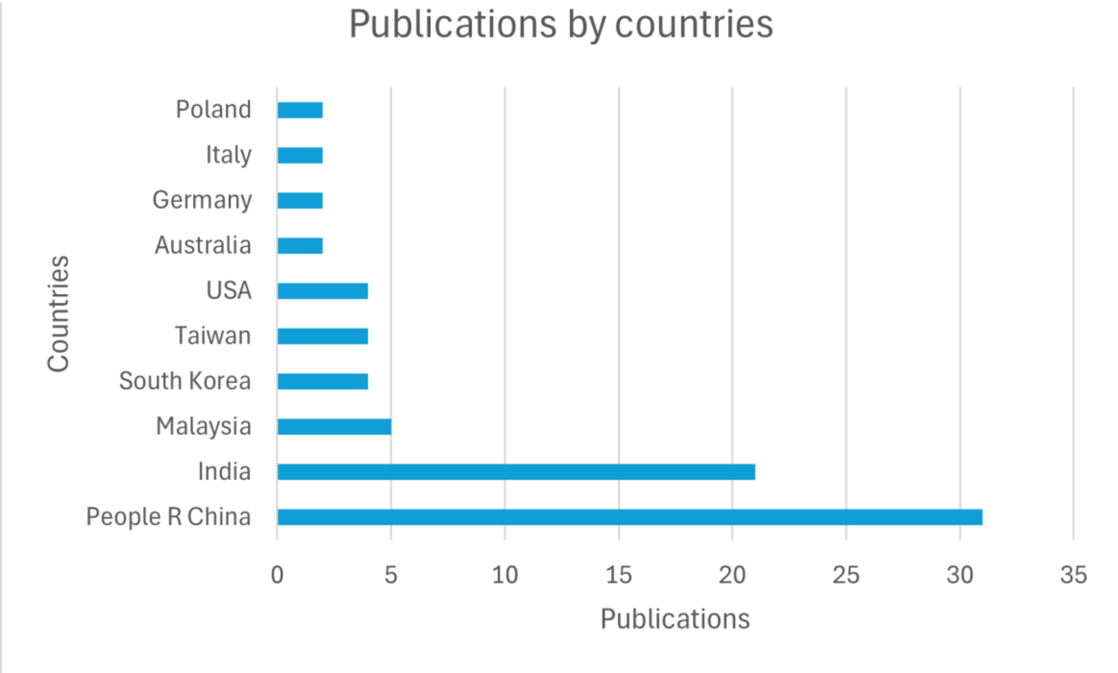

Fig. 4. Top contributing countries by WoS document count
Source: Data retrieved from WoS

Keyword Analysis

For better understanding on the research patterns, a co-occurrence map of author keywords was created using VOSviewer. It highlights commonly used terms and emerging topics related to PVDF-HFP polymer electrolytes in electrochemical energy storage research.

This VOSviewer network visualization from Scopus database, which is based on figure 5, effectively maps the co-occurrence of terms associated with PVDF-HFP polymer electrolytes in the energy storage domain, exposing discrete research clusters and their relationships. The mapping has 117 items in 18 clusters, resulting in 326 linkages and an overall link strength of 345. There are varying colours that represent each cluster such as red, green, purple, light brown and more. The largest and core node, “gel polymer electrolyte”, is readily paired with a substantial cluster around “pvdf-hfp”, which is further linked to “energy storage” and “supercapacitor” applications, indicating its fundamental function. Regarding “ionic conductivity”, which is associated with “solid-state batteries” and “composite solid-state electrolytes”, another notable cluster emphasizes attempts to enhance ion transport in these systems.

While “interfacial engineering” also stands out as a significant application linked through the broader “polymer electrolyte” concept, “lithium battery” and “hybrid electrolyte” are prominently linked nodes to “pvdf-hfp”, highlighting their status as primary and emerging application or research areas for PVDF-HFP-based electrolytes, respectively. In addition, the link strength between “gel polymer electrolytes” and “polymer electrolytes” with “pvdf-hfp” are 2. As for nodes “hybrid electrolyte”, “quasi-solid polymer electrolyte”, “organogel electrolyte”, “hybrid solid electrolytes” have link strength of 1 with “pvdf-hfp”. For application of electrochemical devices, there are various keywords that link to PVDF-HFP, such as “lithium-ion battery”, “all solid-state lithium batteries”, “lithium battery”, “sodium metal batteries”, “dual ion batteries” have link strength of 1. Conversely, “supercapacitor” nodes exhibit link strength of 2 with

PVDF-HFP which demonstrates a strong linkage. This indicates that the current research mainly focuses on these stated electrochemical devices.

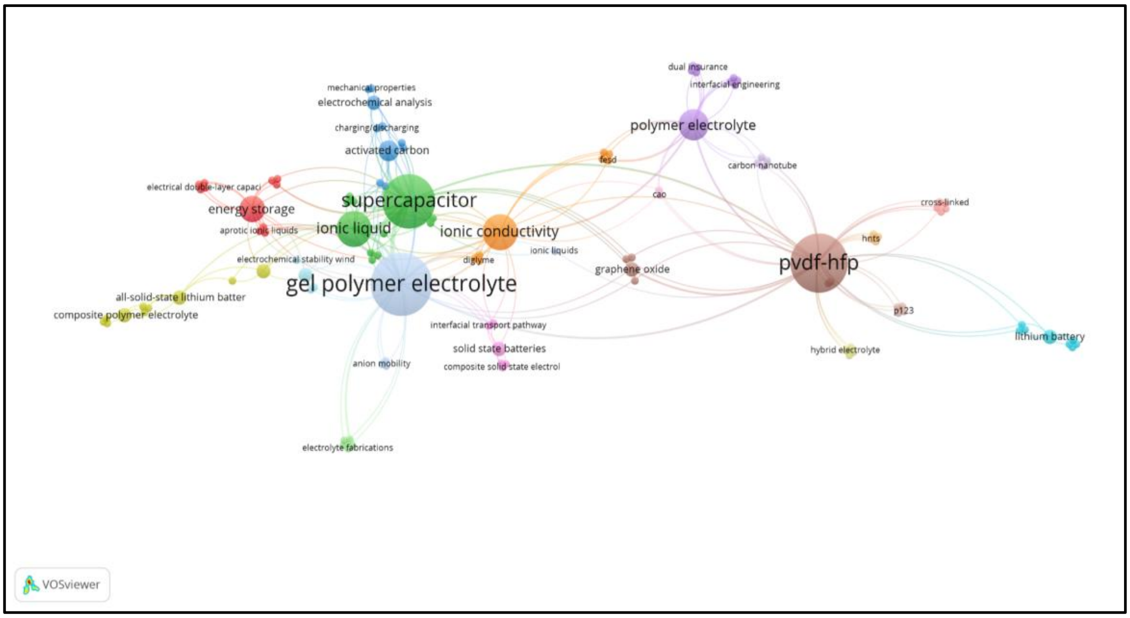

Fig. 5. Keyword co-occurrence network of author keywords related to PVDF-HFP polymer electrolytes for electrochemical devices (2015-2025), generated using VOSviewer based on Scopus data

Table 3 presents the seven keywords with highest occurrence in VOSviewer for Scopus database. Even though the node of “gel polymer electrolytes” (blue) has the same link count with “pvdf-hfp” (light brown) which is 38 but different in total link strength and occurrence. Thus, this implies that the keyword “gel polymer electrolytes” are highly connected and frequently cited with other keywords in the research. In the aspect of electrochemical devices, “supercapacitor” is identified as the most focused keyword in the research field with the strongest occurrence, number of links, and overall link strength. Additionally, the keyword also recorded as the third highest occurrence among all keywords. Therefore, this suggests that the majority of PVDF-HFP polymer electrolyte research is focused on enhancing performance in supercapacitor technologies.

Table 3. Keywords with high occurrence number in VOSviewer for Scopus

Cluster	Keyword	Links	Total link strength	Occurrence
12	Gel polymer electrolyte	38	47	12
8	PVDF-HFP	38	42	11
2	Supercapacitor	29	40	10
7	Ionic conductivity	23	25	6
2	Ionic liquid	18	24	6
5	Polymer electrolyte	20	22	5
1	Energy storage	16	16	4

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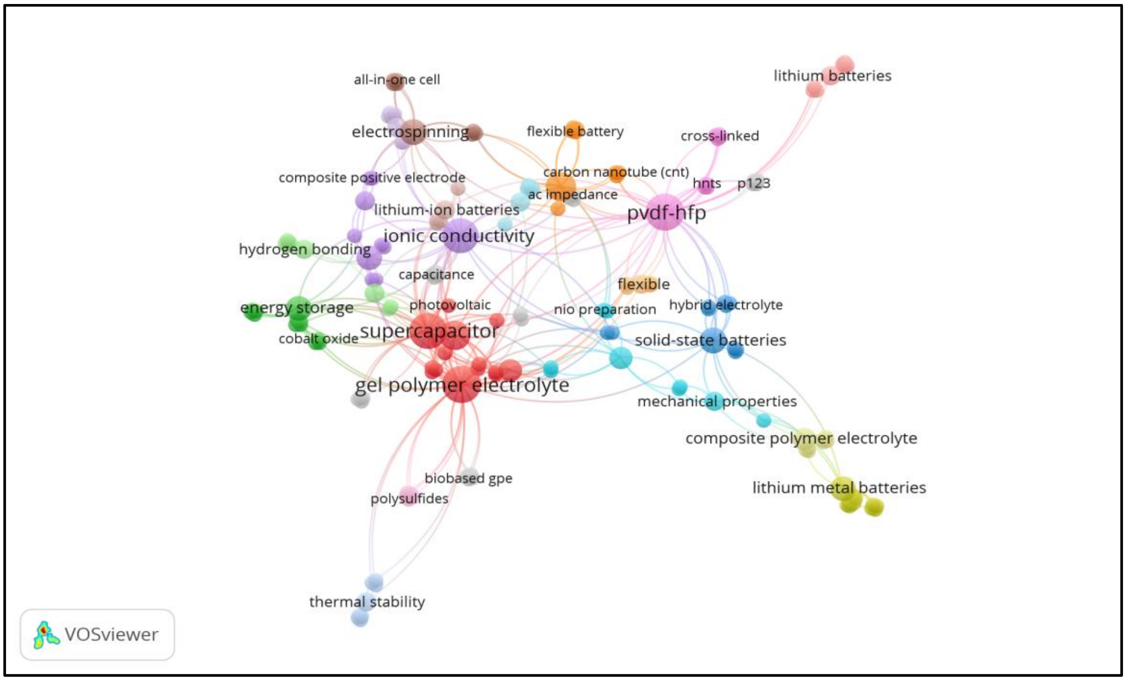

Fig. 6. Keyword co-occurrence network of author keywords related to PVDF-HFP polymer electrolytes for electrochemical devices (2015-2025), generated using VOSviewer based on WoS data

Figure 6 presents a co-occurrence map of author keywords derived from the WoS database, illustrating the frequency patterns and conceptual linkages among keywords within polymer electrolyte research. A total of 173 keywords is divided into 24 clusters, resulting in 489 linkages and overall link strength of 519. Similarly, as Scopus result, WoS mapping for clusters' colour also varies such as red, green, purple, blue and more. From the map, "PVDF-HFP" keyword appears in Cluster 9 with links of 42, total link strength of 50 and 13 occurrences. The link strength between "gel polymer electrolyte" and "polymer electrolyte" with "PVDF-HFP", both have link strengths of 3, respectively, indicating that these keywords are actively studied together. Consistent with Scopus result, WoS also noted "gel polymer electrolyte" as the largest nodes in the mapping. On the other hand, "organogel electrolyte", "quasi-solid-state polymer electrolyte", "hybrid electrolyte", "intercalated composite solid electrolyte" each have link strength of 1 with "PVDF-HFP" as this corresponds to a less association of those keywords.

For electrochemical devices, there are several keywords that link to PVDF-HFP. For instance, between "PVDF-HFP" and "supercapacitor", "lithium-ion batteries", "lithium batteries", "electrochemical double-layer capacitor", "dual-ion batteries", "free standing electrode", "flexible capacitor", "sodium metal batteries", all these keywords have the link strength of 1, respectively. On the other hand, "solid-state batteries" have the link strength of 2 with "PVDF-HFP". These electrochemical devices link strength with PVDF-HFP shows active research on these specific devices.

Table 4 presents the most commonly appearing terms from the WoS database, emphasising major research trends in PVDF-HFP-based polymer electrolytes. As previously stated, “gel polymer electrolyte” appears as the most prominent term, with the greatest frequency, number of links and total link strength, showing that this type of polymer receives substantial attention in the literature. This trend reflects the increased interest in gel polymer electrolytes, which have favourable characteristics for electrochemical applications. Furthermore, in terms of application, "supercapacitor" is the most prominent emphasis area, with high values for occurrence, linkage and total link strength in the whole map but compared to “solid-state batteries”, they have less numbers of link strength with “PVDF-HFP”.

Table 4. Keywords with high occurrence number in VOSviewer for WoS.

Cluster	Keyword	Links	Total link strength	Occurrence
1	Gel polymer electrolyte	45	57	14
	Supercapacitor	38	50	12
	Ionic liquid	18	28	7
2	Energy storage	17	17	4
3	Solid-state batteries	17	18	5
4	Lithium metal batteries	13	14	4
5	Ionic conductivity	33	40	11
	Sodium-ion batteries	11	13	4
6	Electrochemical analysis	6	11	3
7	Polymer electrolyte	25	28	7
8	Electrospinning	20	20	5
9	PVDF-HFP	42	50	13

Relations between Scopus and Web of Science

Between 2015 and 2025, both Scopus and WoS show a similar overall trend in the increase of publications concerning PVDF-HFP polymer electrolytes based on Figure 7. In both databases, research activity began at a modest level in 2015 and steadily grew over time, demonstrating the growing academic interest in energy storage materials. The most noteworthy resemblance is the peak in 2014, when both databases record their highest number of publications which are 13 in Scopus and 14 in WoS, indicating a global increase in research production that year. However, certain discrepancies have been identified. Scopus data indicates more volatility, with notable ups and downs in some years, for example 2020 and 2023, whereas WoS shows a more consistent year-over-year gain, particularly from 2018 to 2022. Furthermore, Scopus indexes more papers in previous years than WoS, probably due to its greater journal and conference coverage. Although the datasets differ, both show a consistent rising trend, emphasising the growing relevance of PVDF-HFP as polymer electrolyte in electrochemical energy storage research.

The regional distribution of publications shows that China contributes the highest number of papers in both databases, followed by India. However, some differences emerged between the two databases. Significant regional contributions to polymer electrolyte research are reflected in the greater representation of Asian countries in WoS, including Taiwan, South Korea, and Malaysia. Compared to the Asian region, countries such as Australia, Germany, Italy, and Poland have lower numbers of publications. While Scopus offers wider geographical coverage, WoS also highlights both leading research countries. This clarifies countries with limited representation in the WoS, such as Ethiopia and Czech Republic, appear in the Scopus dataset.

Furthermore, the occurrence mapping of VOSviewer reveals both similarities and differences in the patterns, keywords usage, and thematic emphasis between the Scopus and WoS databases. Notably, the term “gel polymer electrolyte” consistently ranks as the most frequently cited author keywords in both databases with 14 and 12 occurrences in WoS and Scopus respectively. Furthermore, the mapping also underscores the relevance of PVDF-HFP polymer electrolytes in energy storage applications. This can be seen through their strong relations with supercapacitor technologies with 12 occurrences in WoS while

Scopus with 10 occurrences. Overall, the results show that Scopus and WoS focus on similar topics and both highlight PVDF-HFP as key to improving future electrochemical energy systems.

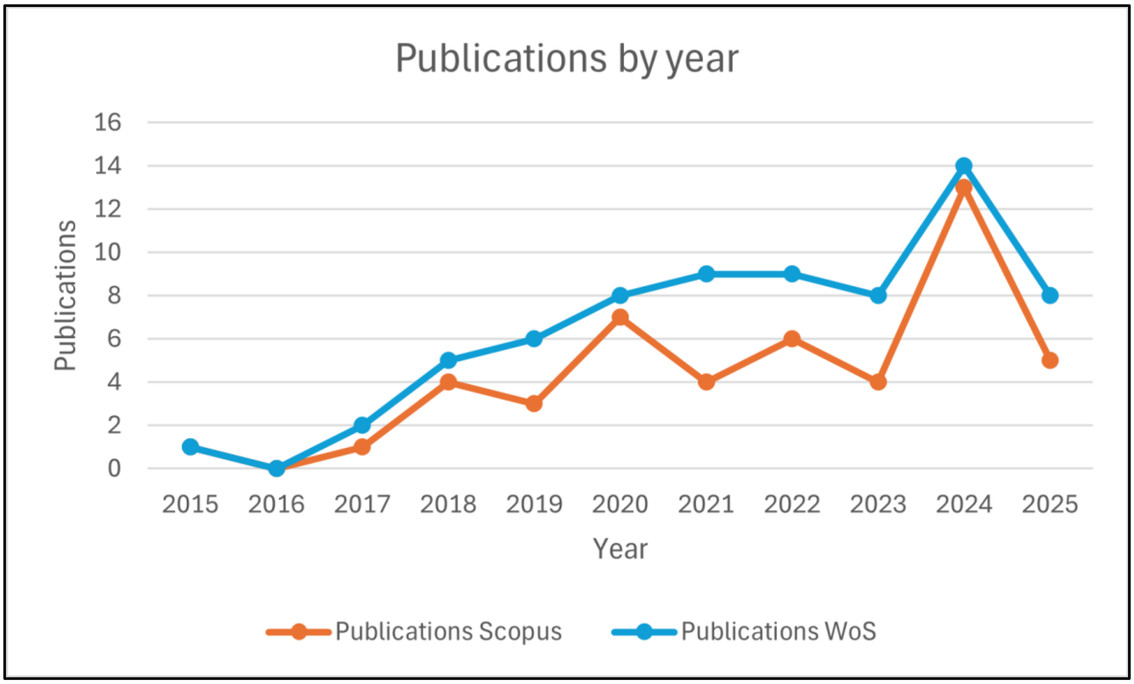

Fig. 7. Comparison publications by year of Scopus and WoS

CONCLUSION

This bibliometric analysis of PVDF-HFP polymer electrolytes in electrochemical energy storage devices highlights substantial progress and increasing scholarly interest in the field, particularly in areas such as ionic conductivity enhancement, material stability, and synthesis optimization. The results show that China and India have emerged as leading contributors, advancing research focused on applications including Lithium-ion batteries, gel polymer electrolytes, and supercapacitors. Among the various synthesis techniques explored, sol-gel processing, electrospinning, and solution casting have demonstrated notable improvements in conductivity and performance. Each of them is modified to specific device requirements. Keyword analysis from VOSviewer further strengthens the prominence of “gel polymer electrolyte” and “PVDF-HFP” as central themes reflecting their importance in current research. Collectively, this study unites the existing knowledge, identifies promising directions for future investigation, and provides valuable guidance for advancing material selection and electrochemical performance in next-generation energy storage systems.

Beyond summarizing the current landscape, the findings of this bibliometric mapping highlight several promising directions for future research. The co-occurrence study demonstrates that supercapacitor is currently the most prominent and trending keyword connected with PVDF-HFP, indicating a high global interest in its energy storage applications. This suggests that researchers can strategically align their work with this trend to increase visibility and impact in this research. At the same time, the mapping emphasizes the relevance of lithium battery research, which is still an essential part for developing polymer electrolyte technology. Expanding publications in both domains, supercapacitors and lithium batteries, would not only increase the knowledge base but also encourage innovation in PVDF-HFP and polymer electrolyte investigations, ultimately aiding in the development of next-generation energy devices.

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Second, future research could focus on the development of composite polymer electrolytes. Incorporating passive or active fillers into the polymer matrix, such as carbon nanotubes, hybrid fillers, titanium dioxide, and silicone dioxide, has the potential to improve ionic conductivity, mechanical strength, and electrochemical performance. Furthermore, biobased gel polymer electrolytes are a potential and sustainable option that deserves additional exploration. Exploring these opportunities will not only widen the scope of PVDF-HFP research but also help to advance environmentally friendly and high-performance polymer electrolyte systems.

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Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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