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Bibliometric Analysis of Polyethersulfone (PES) Membrane Research Development (2012-2022) Using Publish or Perish and VOSviewer

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Abstract

Purpose: Polyethersulfone (PES) membranes are widely used in filtration and gas separation due to their strong thermal, mechanical, and chemical stability. However, no comprehensive bibliometric mapping of PES membrane research has been conducted. This study aims to analyze publication trends, research quality, influential works, and thematic evolution in PES membrane literature from 2012 to 2022.

Methodology: Bibliometric data were retrieved from Google Scholar using Publish or Perish with keywords related to Chemistry, Particle, PES, and Membrane, covering 1,000 articles (2012–2022). VOSviewer was used for analysis through network visualization (co-word clustering), overlay visualization (temporal trends), and density visualization (research intensity). A minimum co-occurrence threshold of five keywords produced 170 significant terms.

Results: Publications increased from 55 in 2012 to 123 in 2020, averaging about 90 papers annually. Of 1,000 articles, 77.8% were published in Q1 journals, with Elsevier contributing 61.4%. Eight thematic clusters were identified, highlighting mixed matrix membranes and MOF-based membranes as dominant research directions.

Conclusions: PES membrane research shows strong growth and high publication quality, evolving toward advanced mixed matrix and MOF/COF-based membrane technologies.

Limitations: The dataset is limited to Google Scholar, partial 2022 coverage, and keyword constraints that may exclude relevant studies.

Contributions: This study provides the first bibliometric baseline for PES membrane research, mapping trends, quality distribution, and thematic evolution to guide future research directions.

Keywords: *Bibliometric Analysis, Mixed Matrix Membrane, Polyethersulfone Membrane, Scientific Mapping, VOSviewer*

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1. Introduction

Polyethersulfone (PES) has emerged as one of the most strategically important polymeric materials in membrane science and industrial separation technology. Its combination of high glass transition temperature, broad chemical resistance, excellent mechanical strength, and reliable film-forming behavior through the phase inversion process has made it the polymer of choice for manufacturing ultrafiltration, microfiltration, and nanofiltration membranes across water treatment, pharmaceutical processing, food manufacturing, and gas separation sectors (Alkhudhiri, Darwish, & Hilal, 2012; Khorshidi, 2016; Rajaeian, Heitz, Tade, & Liu, 2013). PES is synthesized from bisphenol A and 4,4-dichlorodiphenyl sulfone through condensation polymerization via aromatic nucleophilic substitution, yielding an amorphous thermoplastic polymer with a glass transition temperature exceeding 220 degrees Celsius. These thermal and chemical properties allow PES membranes to withstand sterilization protocols, elevated operating temperatures, and exposure to solvents that would degrade less robust polymer matrices (Khorshidi, 2016; Ghaemi, Madaeni, Daraei, Rajabi, Zinadini, Alizadeh, Heydari, Beygzadeh, & Ghouzivand, 2021).

Despite these substantial practical advantages, PES membranes carry a well-documented limitation rooted in their intrinsically hydrophobic surface chemistry. The aromatic sulfone backbone of PES promotes adsorption of hydrophobic solutes, organic macromolecules, proteins, oil droplets, and bacteria onto the membrane surface, triggering fouling processes that progressively reduce permeate flux, increase transmembrane pressure, and shorten service life (Rahimpour, Jahanshahi, Khalili, Mollahosseini, Zirepour, & Rajaeian, 2012; Asad, 2020; Susanto, & Ulbricht, 2022). Fouling not only increases operational costs through more frequent cleaning cycles and earlier membrane replacement, but also introduces variability into separation performance that complicates process control. These challenges have sustained decades of research into PES modification strategies ranging from surface coating and grafting to nanoparticle incorporation and the engineering of sophisticated composite architectures.

The volume of PES membrane research literature has expanded dramatically over the past decade. This expansion reflects both the growing industrial deployment of PES membranes in new application contexts and the rapid proliferation of novel modification strategies enabled by advances in nanomaterials synthesis, polymer chemistry, and crystalline porous framework materials. The resulting literature is large, multidisciplinary, and increasingly complex, spanning surface chemistry, composite membrane engineering, gas separation physics, environmental remediation, and the synthesis of advanced filler materials including Metal-Organic Frameworks (MOFs) and Covalent Organic Frameworks (COFs). For researchers seeking to enter the field, position new research contributions, or identify the most productive directions for future work, navigating this literature without systematic analytical support is both time-consuming and unreliable (Ding & Yang, 2022).

Bibliometric analysis offers a rigorous, reproducible, and scalable methodology for characterizing the intellectual structure of large research domains. By analyzing patterns of publication volume, citation frequency, and keyword co-occurrence across extensive document sets, bibliometric studies can reveal the dominant and emerging thematic clusters within a field, characterize the quality distribution of publication venues, identify the most influential foundational works, and track the temporal evolution of research priorities in ways that manual literature review cannot efficiently replicate (Broadus, 1987; Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021a; Ding and Yang, 2022). These capabilities are particularly valuable in applied fields such as membrane science, where technological development trajectories are tightly coupled to recent literature advances and where the volume of annual publications exceeds what any individual researcher can comprehensively monitor.

VOSviewer, developed at Leiden University, has become the leading software tool for bibliometric scientific mapping through its ability to construct and visualize network maps of co-word, co-citation, and bibliographic coupling relationships and to enrich these maps with temporal information through overlay and density visualization modes (van Eck & Waltman, 2010; Ding and Yang, 2022). Publish or Perish complements VOSviewer as a freely available application enabling systematic bibliometric data retrieval from Google Scholar at scale (Harzing, 2007). Together, these tools have been validated across a range of materials science and chemical engineering bibliometric studies as capable of producing cluster structures and temporal patterns consistent with those obtained from subscription-database sources (Fauzi, Nandiyanto, & Ragadhita, 2023; Zulherman, Nandiyanto, & Ragadhita, 2022; Al, & Nandiyanto, 2022).

Despite the recognized importance of PES membranes as a research subject and the availability of established bibliometric tools, no systematic bibliometric study of the PES membrane domain had previously been conducted. This study addresses this gap by providing the first comprehensive bibliometric analysis of 1,000 PES membrane articles published between 2012 and 2022. The analysis documents the sustained growth trajectory of the field, characterizes its high concentration in Q1 publication venues, identifies the ten most-cited works anchoring its intellectual structure, and maps the eight-cluster thematic architecture revealed by co-word network analysis. The temporal overlay and density visualizations document a clear research evolution from foundational surface modification and antifouling research toward advanced composite and mixed matrix membrane architectures incorporating MOF, COF, and other sophisticated filler materials. The results provide both a quantitative baseline for assessing future developments in PES membrane science and a practical map of the field's thematic geography that researchers can use to identify productive positioning opportunities.

2. Literature Review

2.1 Polyethersulfone Membranes: Chemistry, Fabrication, and Modification

PES membranes are most commonly fabricated through the phase inversion process, in which a homogeneous PES solution in a polar aprotic solvent such as N-methyl-2-pyrrolidone or dimethylformamide is cast as a thin film onto a support and immersed in a non-solvent coagulation bath, typically deionized water (Khorshidi, 2016; Ghaemi et al., 2021). The thermodynamic exchange between solvent and non-solvent during immersion induces polymer precipitation in a controlled manner, producing an asymmetric membrane structure with a dense, selective skin layer on the top surface supported by a porous macrovoid-containing sublayer beneath. The performance characteristics of the resulting membrane depend on a complex interplay of variables in the casting solution including PES concentration, choice of solvent and co-solvent, type and concentration of pore-forming additives such as polyvinylpyrrolidone or polyethylene glycol, casting solution temperature, and the composition and temperature of the coagulation bath (Rahimpour et al., 2012; Alenazi et al., 2017).

The modification of PES membranes to overcome their hydrophobic fouling susceptibility has followed two broad and sometimes complementary pathways. Surface modification addresses the hydrophobicity problem directly at the membrane surface without altering the bulk polymer matrix. Techniques in this category include polydopamine coating, which exploits the universal adhesion of oxidatively polymerized dopamine-derived films to deposit hydrophilic functional layers on virtually any substrate; UV-induced surface grafting of hydrophilic monomers such as acrylic acid, methacrylic acid, or hydroxyethyl methacrylate; plasma treatment to generate reactive surface groups for subsequent hydrophilic functionalization; and chemical crosslinking with polyethylene glycol or other hydrophilic agents (Alenazi et al., 2017; Susanto & Ulbricht, 2022; Asad, 2020). These approaches produce measurable improvements in surface wettability and fouling resistance, but their effects are primarily confined to the membrane surface and may diminish with extended operation as surface coatings weather or grafted chains conform away from the surface in dry storage conditions.

Bulk modification strategies address PES membrane performance at a more fundamental level by altering the composition of the casting solution itself. Polymer blending incorporates hydrophilic polymers such as PVP, PEG, or polyvinyl alcohol directly into the PES matrix, producing membranes with increased surface hydrophilicity and modified pore structures Rajaeian et al., 2013. Nanoparticle incorporation creates composite membranes by dispersing inorganic particles including TiO2, SiO2, Fe3O4, ZnO, silver nanoparticles, and graphene oxide into the casting solution, yielding nanocomposite membranes with simultaneously improved hydrophilicity, permeability, selectivity, and in some cases antibacterial activity (Arsuaga et al., 2013; Ayyaru & Ahn, 2018; Kiran et al., 2016). The most recent generation of PES composite membranes employs MOFs and COFs as multifunctional fillers, leveraging their well-defined crystalline pore structures to provide both improved transport selectivity and functional surface chemistry that conventional inorganic particles cannot replicate (Bagherzadeh et al., 2020; Jiang et al., 2022; Zornoza et al., 2021).

2.2 Bibliometric Analysis as a Research Methodology

Bibliometric analysis is a quantitative method for characterizing the published literature of a research domain using secondary publication data. Its key analytical dimensions include publication counts and growth trends that measure the scale and trajectory of research activity in a domain, citation analysis that identifies the most influential works and their intellectual lineage, keyword co-occurrence analysis that reveals thematic clusters and their interconnections, author and institutional co-authorship analysis that maps collaboration networks, and journal analysis that characterizes the publication venue landscape (Broadus, 1987; Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021a). The bibliometric approach produces results that are quantitative, reproducible across independent analysts using the same dataset, and scalable to corpus sizes that exceed the practical limits of manual review, making it particularly suitable for mapping large, rapidly growing research fields where comprehensive narrative review is no longer feasible for individual researchers (Ding, & Yang, 2022; (Donthu, Kumar, Pattnaik, & Lim, 2021b)).

Co-word analysis, the bibliometric mapping technique applied in this study, identifies thematic clusters by analyzing the frequency with which pairs of keywords co-occur across a document corpus. Keywords that appear together frequently in multiple publications form strong network links and tend to cluster in the resulting VOS viewer network visualization, defining groups that represent coherent research sub-fields or methodological traditions within the broader domain (Chang, Huang, & Lin, 2015; Ding and Yang, 2022). The resolution of cluster detection is controlled by the minimum co-occurrence threshold: lower thresholds include more terms and reveal finer-grained thematic structure at the cost of greater network complexity, while higher thresholds filter to only the most central and strongly connected terms and produce cleaner maps with reduced noise. The threshold of five occurrences applied in this study reflects a balance between thematic completeness and map legibility that has been validated in comparable bibliometric studies of polymer and membrane research domains (Fauzi, Nandiyanto, & Ragadhita, 2023; Ratna, Nandiyanto, & Ragadhita, 2022; Fauzi et al., 2023).

The overlay visualization extends the co-word network map with a temporal dimension by color-coding each keyword node according to the average publication year of articles in which it appears. This visualization distinguishes between foundational research themes, represented by blue and green nodes corresponding to keywords predominantly appearing in earlier publications, and emerging research frontiers, represented by yellow and orange nodes corresponding to keywords predominantly appearing in more recent publications (Handoko, Nandiyanto, Fiandini, & Ragadhita, 2022; Ding and Yang, 2022). The density visualization complements the network and overlays maps by applying a kernel density function across the keyword network, producing a heat-map representation where darker areas indicate higher local concentrations of keyword nodes, pointing to the most intensively and comprehensively studied topic areas within the field. Together, these three visualization modes provide complementary perspectives on the thematic structure, temporal evolution, and research intensity distribution of a domain that no single visualization alone can fully capture.

2.3 Prior Bibliometric Applications in Membrane and Materials Science

Bibliometric analysis has been applied to a growing range of polymer membrane and materials science sub-fields in recent years, providing precedents and comparison baselines for the methodology and findings of the present study. Nandiyanto et al. (2023) conducted a bibliometric mapping of carbon nanotube research using VOSviewer and identified cluster structures and temporal evolution patterns methodologically analogous to those found in PES membrane research, confirming the transferability of the PoP-VOSviewer methodology across applied materials science domains. Zulherman et al. (2022) mapped the bibliometric structure of silver nanoparticle synthesis research, documenting rapid growth patterns and thematic clustering consistent with those observed in the PES membrane overlay analysis reported here. Al Husaeni and Nandiyanto (2022) provided a comprehensive methodological guide to the PoP-VOSviewer workflow that has been widely adopted for bibliometric studies in Indonesian research institutions.

In the membrane science literature specifically, Ding and Yang (2022) applied VOSviewer to platform research mapping, demonstrating the versatility of the tool for tracking knowledge evolution across time-sensitive technical domains. Liu et al. (2021) conducted a bibliometric review of MOF membrane research that is directly relevant to the MOF-based PES MMM cluster identified in the present study, documenting the rapid rise of MOF fillers across multiple polymer membrane systems. Luque-Martinez et al. (2022) applied bibliometric analysis to wastewater membrane treatment research, providing an application-focused mapping that complements the material-science-oriented PES membrane analysis presented here. Fauzi et al. (2023) mapped chitosan membrane research using the PoP-VOSviewer workflow, producing cluster structures and temporal trends that serve as a methodological parallel for the present PES membrane analysis. Ratna et al. (2022) applied the same methodology to photocatalysis research, confirming the reliability of Google Scholar-based bibliometric mapping for large and heterogeneous research corpora.

3. Research Methodology

3.1 Data Collection and Database Selection

Bibliometric data were collected using the Publish or Perish application version 8 Harzing, 2007, which queries the Google Scholar database to retrieve article-level metadata including title, authors, year, journal, and citation count. The combined keyword search string used was: Chemistry, Particle, PES, Membrane. This search string was constructed to retrieve publications addressing PES membrane materials in the context of chemical and particle science, capturing research on PES membrane synthesis, modification, characterization, and application while limiting retrieval to membrane-relevant references. The search period was restricted to 2012 to 2022, with 2022 data representing January through September 2022 at the time of data collection. The search returned exactly 1,000 articles, which constitute the complete dataset for all subsequent analyses.

Google Scholar was selected as the primary database source for this bibliometric analysis based on three considerations. Its open-access indexing provides broader coverage of the PES membrane literature than subscription databases, including articles from regional and developing-country journals that are systematically underrepresented in Scopus and Web of Science. The Publish or Perish interface provides direct, reproducible access to Google Scholar metadata at scale, enabling systematic collection and export of bibliometric data for large corpora without manual article-by-article retrieval. Prior bibliometric studies in directly comparable domains have confirmed that Google Scholar-based datasets produce cluster structures and temporal evolution patterns consistent with those obtained from Scopus-based datasets, validating the approach for the present application (Nandiyanto et al., 2023; Zulherman et al., 2022; Ratna et al., 2022; Al Husaeni & Nandiyanto, 2022).

3.2 VOSviewer Analysis Parameters

The 1,000-article dataset exported from Publish or Perish was imported into VOSviewer version 1.6.18 (van Eck & Waltman, 2010) for co-word network mapping and visualization. VOSviewer processed the keyword fields from each article record, identifying all unique keyword pairs and their co-occurrence frequencies across the full corpus. A minimum keyword co-occurrence threshold of five was applied, meaning only keywords appearing together in five or more articles were included in the network. This threshold produced 170 primary terms for mapping, balancing thematic completeness with network legibility.

VOSviewer generated three complementary visualization outputs from the co-word data. The network visualization maps keywords as nodes sized proportionally to their occurrence frequency, with connecting lines between nodes whose thickness is proportional to co-occurrence frequency, and with clusters identified through VOSviewer's iterative modularity-maximization algorithm. The overlay visualization applies the same network layout but colors nodes by their average publication year score, enabling visual identification of historically established versus recently emerging research themes. The density visualization applies a kernel density estimation function to produce a heat-map overlay on the network, with darker shading in areas of higher keyword node concentration indicating the most intensively researched topic areas within the field. Annual publication counts were tabulated by extracting year fields from the Publish or Perish dataset. Publisher quality was assessed by cross-referencing each article's journal of publication with the Scimago Journal Ranking (SJR) Q1 designation for the corresponding publication year. Top cited publications were identified by sorting the dataset by citation count in descending order, with all counts reflecting data as of September 2022.

4. Results and Discussions

4.1 Annual Publication Trends (2012 to 2022)

Table 1. Annual PES membrane publication count and associated research trends (2012 to 2022, n = 1,000)

Year	Articles	Notable Research Trend
2012	55	Baseline year; surface hydrophilicity enhancement and early antifouling research dominant
2013	61	Rise in nanocomposite membranes; graphene oxide and metal oxide particle incorporation
2014	74	Continued UF and MF application growth; TiO_2 and ZnO blending studies proliferate
2015	95	Antifouling strategies intensify; palm oil mill effluent treatment applications emerge
2016	83	Graphene oxide-embedded PES membranes; industrial wastewater treatment studies
2017	111	Nano hybrid membranes peak; double-stage filtration systems; SiO_2 and ZnO composites
2018	96	Silver nanoparticle membranes; sulfonated TiO_2 composites; polydopamine modification grows
2019	85	MOF integration begins; gas separation membrane studies grow; COF filler studies emerge
2020	123	Highest publication year; mixed matrix membranes dominant; forward osmosis applications
2021	119	Continued MMM development; metal-organic framework fillers; gas separation performance
2022*	83*	Through September 2022 only; continued growth trajectory projected for full year
Average	~90/yr	Sustained growth confirming PES membrane research as an active and expanding domain

Table 1 presents the annual publication counts and associated research trend notes for PES membrane research across the full 2012-2022 study period. The data reveal a clearly positive growth trajectory with sustained momentum, growing from a baseline of 55 articles in 2012 to a peak of 123 articles in 2020, representing a 123.6% increase over eight years. The average publication rate across the study period is approximately 90 articles per year, confirming that PES membrane research constitutes an active and robustly sustained scientific effort. The data pattern also reveals important year-to-year dynamics that reflect the successive emergence of new research sub-fields rather than a simple linear growth trend.

Three distinct growth phases characterize the publication trend. The first phase from 2012 to 2015 reflects early growth driven primarily by expanding interest in nanoparticle-modified PES membranes, coinciding with the broader nanotechnology wave in materials science that made graphene oxide, metal oxide nanoparticles, and carbon nanotubes widely accessible as composite membrane additives. This period produced several of the most highly cited publications in the dataset, including the foundational work by Arsuaga et al. (2013) on metal oxide nanocomposite UF membranes that established core methodology for the nanocomposite sub-field (Arsuaga et al., 2013; Zhang et al., 2013).

The second phase from 2016 to 2018 shows sustained but fluctuating output as nanocomposite approaches matured and researchers began exploring more sophisticated composite architectures. The emergence of graphene oxide-embedded membranes for industrial effluent treatment (Kiran, Thuyavan, Arthanareeswaran, Matsuura, & Ismail, 2016), silver nanoparticle membranes for antibacterial applications, and polydopamine-mediated composite modification strategies reflects the broadening of the PES modification toolkit during this period. The third phase from 2019 to 2021 represents the highest-sustained output in the dataset, driven by the explosive growth of mixed matrix membrane research incorporating MOF and COF fillers and the expansion of PES membrane applications into gas separation and forward osmosis (Bagherzadeh et al., 2020; Rezakazemi et al., 2021; Jiang et al., 2022).

The growth pattern observed for PES membrane research is consistent with publication trends documented in bibliometric analyses of related polymer membrane fields. Ding and Yang (2022) found rapid publication growth in platform research domains driven by technology maturation, and Liu et al. (2021) documented analogous growth trajectories in MOF membrane research that directly intersects with the PES MMM cluster identified here. Fauzi et al. (2023) found similar phase-structured growth in chitosan membrane research, with early foundational work followed by rapid diversification into application domains, mirroring the pattern observed for PES membranes.

4.2 Publisher Quality Distribution and Top-Cited Publications

Table 2. Top 10 most-cited publications on PES membrane research (2012 to 2022)

Title (abbreviated)	First Author	Year	Publisher	Citations
Influence of metal oxide particle type, size, and distribution on nanocomposite UF membrane properties	Arsuaga et al. (2013)	2013	Elsevier	221
Aminated-Fe3O4 NPs filled chitosan/PVA/PES dual-layer nanofibrous membrane for Cr(VI) and Pb(II) removal	Koushkbaghi et al. (2018)	2018	Elsevier	141
Polyethersulfone enwrapped graphene oxide porous particles for water treatment	Zhang et al. (2013)	2013	Elsevier	107
Impact of graphene oxide embedded PES membranes for effective distillery effluent treatment	Kiran et al. (2016)	2016	Elsevier	82
Blocking mechanism of PES membrane during ultrafiltration of POME	Said et al. (2015)	2015	Elsevier	67
Performance evaluation of double stage nano hybrid PES/SiO2 and PES/ZnO membranes for oily wastewater treatment	Kusworo and Utomo (2017)	2017	Elsevier	52
High-adhesive superhydrophobic coatings fabricated by in-situ nano-silica growth on PES surface	Zhao et al. (2021)	2021	Elsevier	44
Fabrication and separation performance of PES/sulfonated TiO2 UF membranes for fouling mitigation	Ayyaru and Ahn (2018)	2018	Elsevier	42
PAA grafting onto acrylate-alumoxane/PES mixed matrix membrane for dye removal	Daraei et al. (2013)	2013	Elsevier	38
Forward osmosis performance of PES/PA TFC membrane via GQDs@UiO-66-NH2 particles	Bagherzadeh et al. (2020)	2020	Elsevier	25

Table 2 presents the ten most-cited publications in the PES membrane dataset ordered by citation count. The citation distribution reveals the intellectual anchors of the PES membrane research community and the methodological contributions that have had the greatest lasting influence on how the field develops new membrane systems. The most-cited publication by Arsuaga, Sotto, Martinez, Molina, and Teli (2013) with 221 citations established the foundational understanding of how metal oxide nanoparticle type, size, and distribution affect the transport and rejection properties of nanocomposite UF membranes, providing a comparative experimental framework that has guided subsequent nanocomposite PES research for nearly a decade.

The thematic pattern across the ten most-cited publications is instructive. The top two works both address composite PES membrane architectures combining PES with functional nanoparticles for water treatment and environmental remediation applications, confirming that composite and nanocomposite membrane design has been the most highly rewarded research direction in terms of citation accumulation. Seven of the ten most-cited works address water treatment or environmental remediation applications, while the remaining three address more fundamental aspects of surface chemistry, membrane fabrication, and composite modification. The exclusive presence of Elsevier publications in the top ten reflects the concentration of the most widely read membrane science journals within this publisher's portfolio, particularly the Journal of Membrane Science and Chemical Engineering Journal, which consistently rank among the highest-impact venues for composite and nanocomposite PES membrane research (Donthu, Kumar, Mukherjee, Pandey, & Lim, 2021a; Luque-Martinez, Liang, & Drewes, 2022).

Table 3. Distribution of PES membrane research publications across Q1 publishers (n = 778 of 1,000)

Publisher	Q1 Publications (n = 778)
Elsevier	478 (61.4%)
ACS Publications	114 (14.7%)
Wiley Online Library	94 (12.1%)
Springer	78 (10.0%)
Taylor and Francis	18 (2.3%)
TOTAL Q1 Publications	778 (77.8% of 1,000)

Table 3 presents the distribution of PES membrane publications across Q1-ranked publishers for the 778 Q1 articles in the dataset. The 77.8% Q1 rate across the full 1,000-article dataset is notably high relative to many applied science fields, reflecting the strong institutional basis of PES membrane research in research-intensive universities and the competitive publication standards of the membrane science journal portfolio. Elsevier's 61.4% share of Q1 publications is disproportionate relative to its general scientific publishing market share and reflects the specific strength of journals such as the Journal of Membrane Science, Separation and Purification Technology, Desalination, Chemical Engineering Journal, and the Journal of Hazardous Materials in the membrane science domain.

Elsevier's dominant position with 478 of the 778 Q1 publications (61.4%) reflects the concentration of the most important membrane science journals within a single publisher's portfolio. ACS Publications accounts for 114 Q1 articles (14.7%), primarily through ACS Applied Materials and Interfaces, Industrial and Engineering Chemistry Research, and Environmental Science and Technology. Wiley contributes 94 Q1 articles (12.1%) through the Journal of Applied Polymer Science and Advanced Materials Interfaces. Springer and Taylor and Francis account for the remaining Q1 publications, primarily through Applied Nanoscience, Polymer Reviews, and the Journal of Environmental Science and Health (Luque-Martinez et al., 2022).

4.3 Co-Word Network Analysis: Eight Research Clusters

Table 4. VOSviewer co-word network analysis: Eight-cluster thematic structure of PES membrane research (2012 to 2022)

No.	Primary Theme	Representative Keywords
1	Phase inversion and antifouling	additive, antifouling performance, ceramic membrane, membrane distillation, membrane filtration, oily wastewater, phase inversion, photocatalytic membrane, PVDF membrane, water purification, ZnO
2	Silver nanoparticle and surface chemistry	Ag NP, antibacterial property, chemical cleaning, colloidal particle, humic acid, membrane fouling, microfiltration, nanofiber, PEG, silver nanoparticles, surface chemistry

No.	Primary Theme	Representative Keywords
3	Thin film composite and NF membranes	covalent organic framework, dye removal, interfacial polymerization, membrane bioreactor, NF membrane, osmosis, rejection, TFC membrane, TFN membrane, thin film nanocomposite, TiO2 nanoparticle
4	Mixed matrix membranes and mechanical properties	antifouling, chemical resistance, GO particle, heavy metal, ionic liquid, mechanical strength, MMM, PES matrix, pristine PES membrane, thermal stability
5	MOF-based membranes and oil-water separation	aqueous solution, chemical bonding, foulant, functional group, metal organic framework, MOF, oil water separation, PES membrane matrix, polymer particles, silver particles
6	Gas separation and mixed matrix membranes	CO2/CH4 separation, filler, gas separation, mixed matrix membrane, MOF particle, recent advance, support layer, zeolite
7	Membrane fabrication and structure	chemical interaction, ethersulfone, membrane chemistry, membrane fabrication, membrane structure, PES substrate, polymer membrane
8	Polydopamine and composite modification	fouling resistance, heavy metal ion, high chemical stability, metal, nanofiller, NMP, polydopamine, polysulfone UF, thin film composite membrane

Table 4 show the VOS viewer co-word network analysis of 170 terms meeting the minimum co-occurrence threshold identified eight distinct thematic clusters representing the major research sub-fields within PES membrane science. Table 4 presents each cluster's primary theme and representative keywords, providing a structured map of the intellectual geography of the PES membrane research domain. The eight-cluster structure reveals the multi-dimensional architecture of PES membrane research and captures both its historical foundations and its current frontiers. Clusters 1 and 2 represent the well-established foundational research tracks that defined the field in its early years. Cluster 1 encompasses phase inversion fabrication and antifouling membrane research, anchored by the ZnO and photocatalytic membrane keywords that were among the earliest nanoparticle modification strategies studied in PES membranes. Cluster 2 addresses silver nanoparticle incorporation and surface chemistry, reflecting the sustained research interest in antibacterial PES membranes for biomedical and water treatment applications where microbial fouling presents specific challenges (Rahimpour et al., 2012; Alenazi et al., 2017).

Clusters 3, 4, 5, and 6 collectively represent the composite membrane research trajectory that has driven PES membrane science toward its current state of the art. Cluster 3 focuses on thin film composite and thin film nanocomposite membranes prepared by interfacial polymerization, where PES serves as the porous support for an active polyamide or other selective layer containing functional nanoparticles including TiO_2, COF particles, and graphene quantum dots. Clusters 4 and 5 jointly define the mixed matrix membrane domain, with Cluster 4 emphasizing the mechanical and chemical property improvements that accompany MMM fabrication and Cluster 5 concentrating on the specific application of MOF-based PES MMMs for oil-water separation. Cluster 6 addresses PES-based MMMs for gas separation, a distinct research direction where MOF and zeolite fillers are selected for their size-selective molecular sieving properties in CO_2/CH_4 and other industrially important gas pairs (Rezakazemi et al., 2021; Zornoza et al., 2021; Jiang et al., 2022).

Clusters 7 and 8 address more specialized dimensions of PES membrane science. Cluster 7 focuses on fundamental membrane fabrication processes and structural characterization, including the chemistry of the ethersulfone repeat unit and the polymer-solvent interactions that govern phase inversion structure formation. This cluster provides the materials science foundation that underpins the performance optimization work in all other clusters. Cluster 8 addresses polydopamine-mediated surface and composite modification, a distinct research pathway that has grown substantially in recent years as the versatility of polydopamine's mussel-inspired adhesive chemistry for depositing functional coatings on PES surfaces has become recognized across multiple application contexts (Ghaemi et al., 2021; Susanto & Ulbricht, 2022; Koushkbaghi et al., 2018).

The structural connectivity between Clusters 4, 5, and 6 in the VOSviewer network, mediated by the shared keywords of mixed matrix membrane, MMM, and metal organic framework, confirms that these three clusters together constitute the dominant research paradigm in contemporary PES membrane science. The convergence of polymer processing, inorganic framework chemistry, and application engineering within this interconnected cluster group reflects the interdisciplinary nature of state-of-the-art PES MMM research, where advances in MOF synthesis from materials chemistry are directly enabling new PES membrane performance levels in engineering applications (Bagherzadeh et al., 2020; Jiang et al., 2022; Zornoza et al., 2021).

4.4 Overlay Visualization: Temporal Evolution of Research Themes

The overlay visualization in Figure 3 maps the temporal distribution of PES membrane research themes by color-coding each keyword according to its average publication year across the 1,000-article corpus. Blue and green nodes represent keywords predominantly associated with earlier publications (2012 to 2016), while yellow and orange nodes represent keywords associated with more recent publications (2018 to 2022). The temporal color gradient across the network provides a visual record of how the PES membrane research agenda has shifted over the study period.

The overlay visualization confirms several patterns consistent with the published literature and the bibliometric expectations established by the publication trend analysis. Keywords associated with foundational surface modification and antifouling research appear in cooler blue and green tones, reflecting their predominance in the 2012 to 2016 literature. These include phase inversion, antifouling performance, silver nanoparticles, PEG, surface chemistry, and membrane fouling, which collectively define the Cluster 1 and 2 research space that occupied the majority of PES membrane research output during the early years of the study period (Alenazi et al., 2017; Asad, 2020; Rahimpour et al., 2012).

In contrast, keywords associated with MOF and COF-based membranes, including metal organic framework, MOF, covalent organic framework, gas separation, forward osmosis, and mixed matrix membrane, appear in the warmest yellow and orange tones, confirming their emergence as the most recent research frontiers concentrated in the 2019 to 2022 period. This temporal pattern is consistent with the broader trajectory in polymer membrane science toward using crystalline porous framework materials as multifunctional fillers capable of providing simultaneously improved permeability, selectivity, and antifouling characteristics that conventional nanoparticle fillers cannot deliver (Bagherzadeh et al., 2020; Rezakazemi et al., 2021; Jiang et al., 2022).

An important intermediate temporal zone appears in the overlay map for nanocomposite membrane keywords including TiO2, graphene oxide, ZnO, silver particles, and sulfonated metal oxide particles, which appear in the 2016 to 2019 mid-range color band. This positioning reflects the sustained growth of nanoparticle-modified PES membrane research as a transition between the surface modification era and the more recent MMM-dominated era, and is consistent with the publication trend data showing continued high output from 2015 to 2019 before the MOF and COF research wave elevated the 2020 to 2021 peak (Kiran et al., 2016; Ayyaru & Ahn, 2018; Kusworo & Utomo, 2017). The temporal overlay thus confirms that the field has not simply abandoned earlier research themes but has built successively more complex composite architectures on the foundation established by nanoparticle incorporation strategies.

4.5 Density Visualization: Research Intensity Mapping

Figure 4 presents the VOSviewer density visualization, which maps the relative research intensity across the PES membrane keyword network using a kernel density estimation approach. The heat-map representation produced by this visualization encodes keyword density as a color gradient, with the darkest shaded areas indicating the highest local concentrations of keyword nodes and therefore the most intensively and comprehensively researched topic areas within the PES membrane field.

The density visualization identifies the mixed matrix membrane research cluster as the highest-density region of the PES membrane keyword network, confirming that the engineering of PES polymer matrices incorporating diverse filler materials represents the most intensively and comprehensively studied topic area within the 2012 to 2022 literature. The convergence of composite architecture design, filler material selection, and performance characterization within this high-density region reflects the central role that MMM research has assumed in defining the current state of the PES membrane field. This finding is corroborated by the publication trend data showing the 2020 to 2021 peak coinciding with the most intensive period of MMM research output, and by the overlay visualization showing MMM-related keywords in the most recent publication year color range (Rezakazemi, Amooghin, Montazer-Rahmati, Ismail, & Matsuura, 2021; Jiang, Li, He, Bai, & Shao, 2022; Zornoza, Tellez, Coronas, Gascon, & Kapteijn, 2021).

The density visualization also reveals areas of relatively lower research intensity despite their thematic presence in the network, most notably in the application performance evaluation space where membrane performance in standardized water treatment and gas separation benchmarking tests remains underrepresented relative to materials synthesis and characterization research. This observation is consistent with the broader pattern in applied materials science where synthesis methodology papers consistently outnumber performance benchmarking studies, and suggests that systematic comparative performance evaluation studies comparing different PES MMM compositions in standardized application tests would address a genuine gap in the literature (Liu, Jin, & Xu, 2021; Luque-Martinez, Liang, & Drewes, 2022; Fauzi, Nandiyanto, & Ragadhita, 2023).

The combined evidence from the publication trend analysis, publisher quality assessment, top-citation analysis, co-word network clustering, and overlay and density visualizations converges on a coherent and internally consistent characterization of the PES membrane research domain. The field is mature in terms of its publication quality, with 77.8% Q1 publications confirming strong institutional and editorial standards. It is actively growing in output volume, with the 2020 to 2021 peak driven by the MOF and COF MMM research wave. And it is undergoing a paradigm shift from surface-level modification toward the engineering of sophisticated composite matrix architectures with multifunctional filler materials, a shift that the bibliometric analysis documents with temporal precision and thematic resolution that narrative review alone could not achieve (Ding & Yang, 2022).

5. Conclusions

5.1 Conclusion

This study conducted the first comprehensive bibliometric analysis of PES membrane research published between 2012 and 2022, using 1,000 articles from Google Scholar analyzed through Publish or Perish and VOSviewer. The analysis produced three principal findings of significance to the PES membrane research community. First, PES membrane research is a high-growth, quality-dominated domain: publication output grew 123.6% from 55 articles in 2012 to a peak of 123 in 2020, averaging approximately 90 publications per year across the study period, and 77.8% of all publications appeared in Q1-ranked journals, with Elsevier accounting for 61.4% of Q1 output. The most-cited publication by Arsuaga with 221 citations on metal oxide nanocomposite UF membrane properties anchor the foundational intellectual contribution of the decade, while the second most-cited work by Koushkbaghi et al., with 141 citations, illustrates the field's strong orientation toward environmental remediation applications. Second, VOSviewer co-word network analysis identified eight thematic clusters spanning phase inversion and antifouling, silver nanoparticle surface chemistry, thin film composite and nanofiltration, mixed matrix membrane properties, MOF-based membranes and oil-water separation, gas separation MMMs, membrane fabrication and structure, and polydopamine composite modification. The cluster structure captures both the historical breadth of PES membrane research and the dominant interconnected position of mixed matrix membrane research spanning multiple clusters. Third, temporal overlay mapping documented a clear research evolution from surface modification approaches that dominated the 2012 to 2016 period toward advanced composite and mixed matrix membrane architectures with MOF and COF fillers dominating the 2019 to 2022 period, with density mapping confirming mixed matrix membranes as the most intensively researched current topic area across the entire keyword network.

5.2 Research Limitations

Four limitations constrain the scope and generalizability of the findings. The bibliometric dataset is restricted to Google Scholar as the sole data source, which, while providing broad coverage including non-indexed and regional publications, lacks the citation verification and controlled metadata quality of Scopus and Web of Science. Google Scholar citation counts may include self-citations, grey literature references, and thesis citations that would be excluded from more curated databases, potentially inflating citation scores for certain publications. The 2022 data covers only January through September at the time of collection, underestimating the full-year 2022 publication count by approximately 25 to 30 percent based on the average monthly publication rates observed in 2020 and 2021. This undercount biases the temporal trend analysis toward underrepresenting the most recent research developments in the MOF and COF MMM sub-field. The keyword search string of Chemistry, Particle, PES, and Membrane may not comprehensively retrieve publications using alternative terminologies such as polysulfone membrane, PES hollow fiber membrane, or PES blend, potentially creating systematic undercounting of certain sub-field publications. Finally, the co-word analysis is limited to keyword-level information and does not capture author collaboration networks, institutional or national research patterns, or funding source distributions that would provide a more complete characterization of the social and institutional structure driving PES membrane research.

5.3 Directions and Future Study

Future bibliometric research on PES membranes should address the documented limitations through several development directions. A follow-up analysis using Scopus or Web of Science as the primary data source, extended to cover 2025, with expanded keyword search terms incorporating alternative terminologies for PES membrane research, would provide a more complete and citation-verified map of the field that could serve as a methodological comparison to the Google Scholar baseline established here. Co-authorship network analysis should be incorporated alongside co-word analysis to reveal the institutional and national collaboration patterns driving PES membrane research, particularly the interdisciplinary connections between materials chemistry groups developing MOF and COF filler materials and chemical engineering groups evaluating their performance in membrane fabrication and separation applications. Application performance benchmarking studies comparing different PES MMM compositions across standardized water treatment, gas separation, and industrial filtration test protocols would address the synthesis-application imbalance identified in the density visualization and provide the systematic performance data needed to guide filler selection for specific practical use cases. A comparative bibliometric analysis mapping PES membrane research alongside parallel analyses of competing polymeric membrane materials such as PVDF, polysulfone, and polyimide would provide a competitive landscape map enabling researchers to identify differentiated positioning opportunities. Finally, a user study examining how bibliometric maps of PES membrane research are actually used by researchers to make literature search, topic selection, and collaboration decisions would assess the practical impact of bibliometric tools on research strategy in the membrane science community.

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Author Contributions

SW contributed to conceptualization, data collection, formal analysis, visualization, writing (original draft). ABDN contributed to **s**upervision, funding acquisition, project administration, validation, review and editing.

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