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Evolution of Functional Membranes: A Bibliometric Approach on the Modification from Polymeric to Nanocomposite Systems

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Abstract

Membrane science has become a study that has received significant attention for its use in membrane filtration. The development of membrane science has accelerated with the use of nanotechnology. Various studies on the use of membranes in water treatment filtration have been conducted, but many focus on single materials and separation effectiveness. However, research presenting developments in membrane technology that focus on the shift from the polymeric era to nanocomposites has not been presented. This gap led this study to map the evolution of membrane science as a direction for future research. A total of 13,983 documents obtained from Scopus were analyzed. Open Refine and Microsoft Excel were used for metadata cleaning, while VOSviewer and IIPmaps were used for data visualization. The analysis was conducted to obtain data on the development and distribution of publications, trending keywords, research transitions, and future research directions. The results show that publications increased rapidly in 2010 that line with the increasing use of nanotechnology. Publication and collaboration trends are dominated by China, the United States, and Malaysia. Research transitions also showed three main phases, namely: polymeric foundations (1990-2005), nanocomposite integration (2006-2015), and advanced functionalities (2016-2025). The advanced functionalities phase showed the use of eco-friendly materials and artificial intelligence in the design of multifunctional membranes. This bibliometric study indicates that water treatment membranes have shifted from improving physical properties to using nanomaterials for functional purposes. Consequently, upcoming work ought to prioritize novel combinations of nanomaterials alongside advancements in produced smart filtration systems.

Keywords: Bibliometric approach, functional membrane filtration, polymeric membrane, nanocomposite membrane, sustainable water treatment

INTRODUCTION

Polymer-based membranes have been widely developed for separation applications in wastewater treatment. Various types of polymers that are often used are polyvinylidene fluoride (PVDF), polysulphone (PSF), and polyether sulphone (PES) [1–3]. The characteristics of the membrane are different. PVDF is known for its mechanical strength and chemical resistance, PES for its hydrophilicity and steady performance in water treatment, and PSF for its stability [4]. Membranes can be made from a single polymer [5] or a mixture of polymers [6]. This depends on the desired properties of the membrane. Polymer membranes are widely used as a separation method because they are considered more environmentally friendly and economical, as they do not require chemicals like traditional separation methods. In addition, the separation process is simple, making it easy to use [7,8].

Nonetheless, over time, the waste produced by humans has become increasingly diverse. This has led to the need for more complex membranes to solve existing problems. Furthermore, water pollution has become a global issue, making advanced membranes play an important role in overcoming it. Hazardous materials that cause water pollution, such as dyes, oils, and other dangerous chemicals, can be overcome with the use of membrane technology [9,10]. PVDF membranes are typically used for membrane distillation and hemodialysis [11], PES membranes are typically used for BOD and COD removal [12], while PSf membranes are typically used in conjunction with PVDF to improve performance [13]. Combinations of materials or surface combinations have become alternatives for improving membranes [14,15]. This allows the membrane properties to be adjusted according to the required treatment.

Various types of nanomaterials are considered promising for modifying polymer membranes according to specific requirements. The presence of nanomaterials in membranes can also help overcome major membrane problems, such as membrane fouling [16,17]. Various nanomaterials that are widely used in membranes include: graphene oxide (GO), carbon nanotubes (CNTs), titanium dioxide (TiO_2), silicon dioxide (SiO_2), and, more recently, metal–organic frameworks (MOFs) [18,19]. The use of nanomaterials is tailored to the required properties. For example, SiO_2 prevents agglomeration during nanoparticle mixing [20], TiO_2 helps overcome biofouling and increases photocatalytic activity [21,22], and CNTs help increase water permeability and mechanical strength in membranes [22]. Chen's (2022) research developed TiO_2 and GO-based membranes with poly (arylene ether nitrile) (PEN) as a substrate for faster separation of oil and water emulsions. In addition, polysulfone hollow fibre membranes modified with CNTs and GO have also been developed to produce superior antifouling capabilities [23]. Another study also developed PVDF/SiO_2 membranes with a focus on membrane durability under harsh environments [24]. This demonstrates the influence of nanomaterials on accelerated membrane development and the advantages in application.

In addition to the use of nanomaterials, membrane development has also entered a more advanced stage, for example, with the combination of nanomaterial membranes, photocatalysts, and other light irradiation, which can assist membrane regeneration [25]. Membrane regeneration extends the life of the membrane. In addition, several studies have shown that end-of-life membranes can be reactivated [26]. This entire process can run optimally because the membrane polymer is aided by the presence of nanomaterials in the membrane.

The rapid development of membranes from polymer membranes to combinations has led many researchers to develop literature review articles on membranes. However, current articles focus on specific membrane topics, such as discussing mixed matrix membrane [27], modified PES membrane [28], membrane coated with graphene-based material [29], incorporating a polymeric membrane with metal/metal oxide nanoparticles [30], and a GO-based membrane [31]. Nonetheless, no research has systematically examined the bibliometric evidence regarding the transition from polymer-based membranes to nanocomposite membranes, despite this shift signalling a significant evolution in membrane science over the past 20 years. In the existence of knowledge about the shift in membrane development can help in mapping the membrane that will be developed in the future and knowing the research gap that exists among researchers.

This study presents the development of membrane functionalization over the past three decades. It aims to help map the current development of membranes, their shifts, and the direction of future research. Accordingly, this study pursues four main objectives: (i) to analyze the growth trajectory and global research landscape in membrane science; (ii) to map the thematic structure and conceptual development of the field; (iii) to examine the intellectual foundation and paradigm transition from polymeric to nanocomposite membranes; and (iv) to identify emerging frontiers and future directions that define the discipline's ongoing evolution. In this way, the present work not only gives an overview of research progress from a macroscopic perspective but also presents forward-looking research directions that inspire subsequent membrane innovation.

METHODOLOGY

This research employed a bibliometric approach. The steps were adopted from Donthu et al [32]. Data were obtained from the Scopus database covering the timeframe from 1990 to 2025. A total of 13,983 results were obtained using strings to focus on terms, as shown in Table 1. Subsequently, the results were refined by applying inclusion and exclusion criteria related to language and subject area, as summarised in Table 2. Seluruh data yang didapatkan kemudian diexport ke .csv format yang berisi bibliometric informasi seperti title, authors, affiliations, keywords, and citation counts The data that was not in English and not associated with membrane science were excluded after manual screening.

Table 1. The Search String

Scopus Data searched 10 October 2025	TITLE-ABS-KEY((membrane AND (polymer* OR polymeric OR "polymeric membrane" OR PVDF OR PES OR PSf OR "polyethersulfone" OR "polyvinylidene fluoride" OR nanocomposite OR "nanocomposite membrane" OR "mixed matrix" OR "mixed matrix membrane" OR "graphene oxide" OR GO OR TiO_2 OR SiO_2 OR CNT OR "carbon nanotube" OR MOF OR ZIF OR MXene OR hybrid OR "functional membrane")) AND ("oil-water" OR "emulsion" OR "wastewater" OR "water purification" OR "water treatment" OR "desalination" OR "filtration performance" OR "oil removal" OR "antifouling") AND NOT ("gas separation" OR "gas permeation" OR "proton exchange" OR "fuel cell" OR "proton exchange" OR "biomembrane" OR "drug delivery" OR "tissue" OR "blood"))

Table 2. The Selection Criterion in Searching

Criterion	Inclusion	Exclusion
Language	**English**	**Non-English**
Subject Area	**Membrane Science**	**Besides Membrane Science**

In data analysis, the first step is metadata cleaning and keyword harmonisation. In this case, Microsoft Excel is used to sort raw data, remove duplicate entries, and the data format is ready for analysis. OpenRefine is then used to refine the data by systematising author names, institutions, and keyword terms to achieve high consistency and accuracy in the database. In addition, VOSviewer (version 1.6.20) is used for quantitative bibliometric analysis. After cleaning the data using Open Refine, the data was processed using VOSviewer to obtain network analysis. The data analysed to obtain the relationships was co-occurrence. The co-occurrence data set was divided into three time periods to look at long-term trends: (i) Polymeric Era (1990-2005), (ii) Nanocomposite Transition (2006-2015), and (iii) Hybrid Functional Era (2016-2025). This division enabled the comparison and observation of how the technology in the field has changed over time. Meanwhile, co-authorship and co-citation were analysed descriptively. The results of the analysis of the geographical distribution of publications, which showed patterns of publication between countries, were presented in world maps using IIPmaps.

RESULTS AND DISCUSSION

Publication growth and research dynamics

In general, the distribution of publications for the period 1990–2025 shows a significant increase (Figure 1, Table 3). In the early phase of 1990–1992, the growth in publications reached only 0.08%, 0.11%, and 0.10%, respectively. These results indicate low publication rates, which are consistent with the polymer-based membrane phase [33]. Entering the late 1990s and early 2000s, publications began to increase, reaching 0.66% in 2005. A significant increase in publications occurred in 2015. This can be seen when comparing publications in 2006, which only reached 77 (0.55%), to 476 (3.41%) in 2015. This shows an increase in researchers' interest in the development of membrane science [34,35].

The period from 2006 to 2025 was the most productive in terms of publications, with nearly half of all publications being published during this time frame. The number of publications grew from 569 (4.07%) in 2016 to a peak of 1,640 (11.74%) in 2024, then declined slightly to 1,505 (10.77%) in 2025. This rapid growth indicates that the research ecosystem has matured and is supported by international collaboration, broader methods and technologies [36]. The development of membrane science has transformed from a new branch of science into a stable science. This provides a basis for conducting further analysis of the evolution of membrane science, both thematically and conceptually.

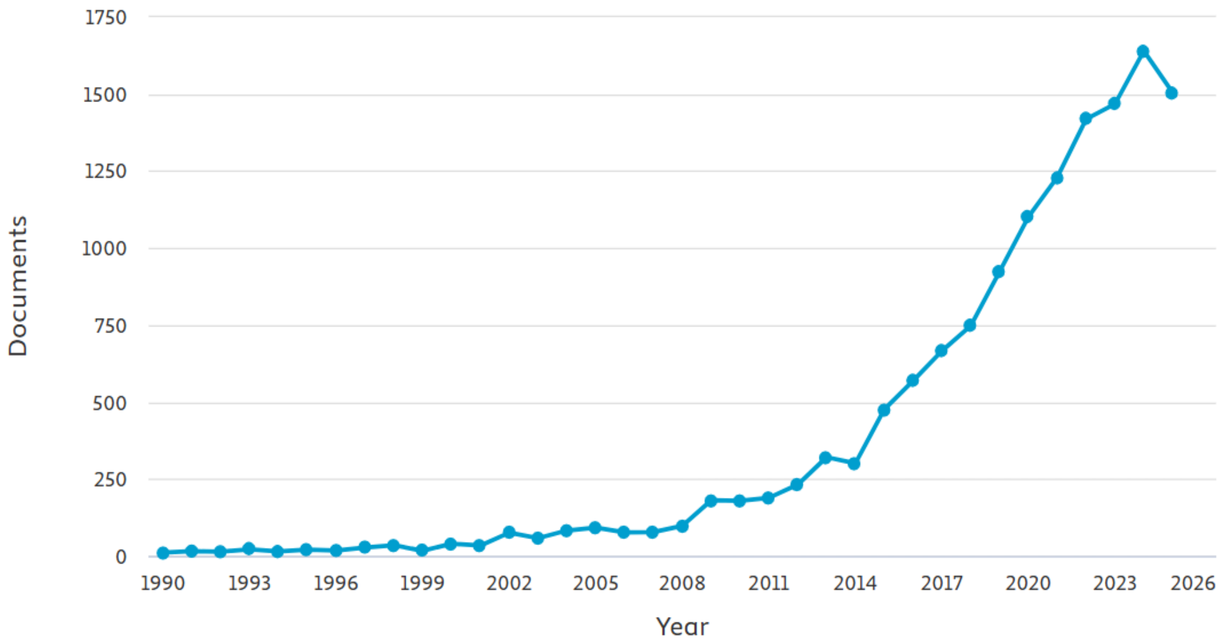

Figure 1 Research trends for the year of publication

Table 3 Year and total of publication

Year	Total Publication	Percentage (%)	Year	Total Publication	Percentage (%)
2025	1,505	10.76	2007	78	0.56
2024	1,640	11.73	2006	77	0.55
2023	1,468	10.50	2005	92	0.66
2022	1,419	10.15	2004	83	0.59
2021	1,230	8.80	2003	58	0.41
2020	1,102	7.88	2002	76	0.54
2019	924	6.61	2001	34	0.24
2018	748	5.35	2000	40	0.29
2017	666	4.76	1999	17	0.12
2016	569	4.07	1998	35	0.25
2015	476	3.40	1997	28	0.20
2014	301	2.15	1996	18	0.13
2013	321	2.30	1995	21	0.15
2012	232	1.66	1994	15	0.11
2011	189	1.35	1993	22	0.16
2010	179	1.28	1992	14	0.10
2009	181	1.29	1991	16	0.11
2008	98	0.70	1990	11	0.08

Leading authors, institutions, and countries

The contributions of researchers, institutions, and countries are presented in Table 4-5 and Figure 2. The researcher with the most significant contribution to the development of membrane separation and its technology is Ismail A.F., with a total of 229 publications to date. This number is followed by other researchers, namely Matsuyama H. (147), Chung T.S. (125), and Liang H. (125). At another level of analysis, namely institutions, publications are dominated by research institutions in Asia. Institutions in China occupy the top three rankings, namely the Ministry of Education of the People's Republic of China (801), the Chinese Academy of Sciences (551) and Tiangong University (371). Surprisingly, an institution in Southeast Asia ranked fourth in the top five, namely Universiti Teknologi Malaysia (305). This pattern of dominance shows the acceleration of membrane research progress, which is well-supported nationally through funding policies in East Asia and Southeast Asia [36].

Among the 125 countries involved in membrane research, China ranks first with 5,513 publications. The second and third places show a decrease in the number of publications by around 80% to 1,293 and 1,141, which are held by the United States and India, respectively. Meanwhile, Australia and European countries are in the middle of the rankings with a decrease in publications of around 50% compared to the United States and India. Geographically, this indicates significant growth in research in the Asian region. This aligns with the development of international collaboration, research investment, and national policy support in the field of technology for clean water and environmental safety [37]. The results of the distribution of leading authors, institutions, and countries provide a basis for mapping scientific collaboration and thematic evolution. The results show that membrane research is concentrated in the Asian continent [23].

Table 4. Top 10 Authors and the number of publications

Rank	Authors	Publications
1	Ismail, A.F.	229
2	Matsuyama, H.	147
3	Chung, T.S.	125
4	Liang, H.	125
5	Gao, C.	124
6	Vatanpour, V.	117
7	Van der Bruggen, B.	116
8	Tang, C.Y.	105
9	Lau.W.J.	100
10	Elimelech, M.	98

Table 5. Top 10 Institutions and the number of publications document

Rank	Institution	Documents
1	Ministry of Education of the People's Republic of China	801
2	Chinese Academy of Science	551
3	Tiangong University	371
4	University Teknologi Malaysia	305
5	Harbin Institute of Technology	259
6	University of Chinese Academy of Sciencec	207
7	Donghua University	184
8	Tongji University	178
9	Tsinghua University	177
10	National University of Singapore	169

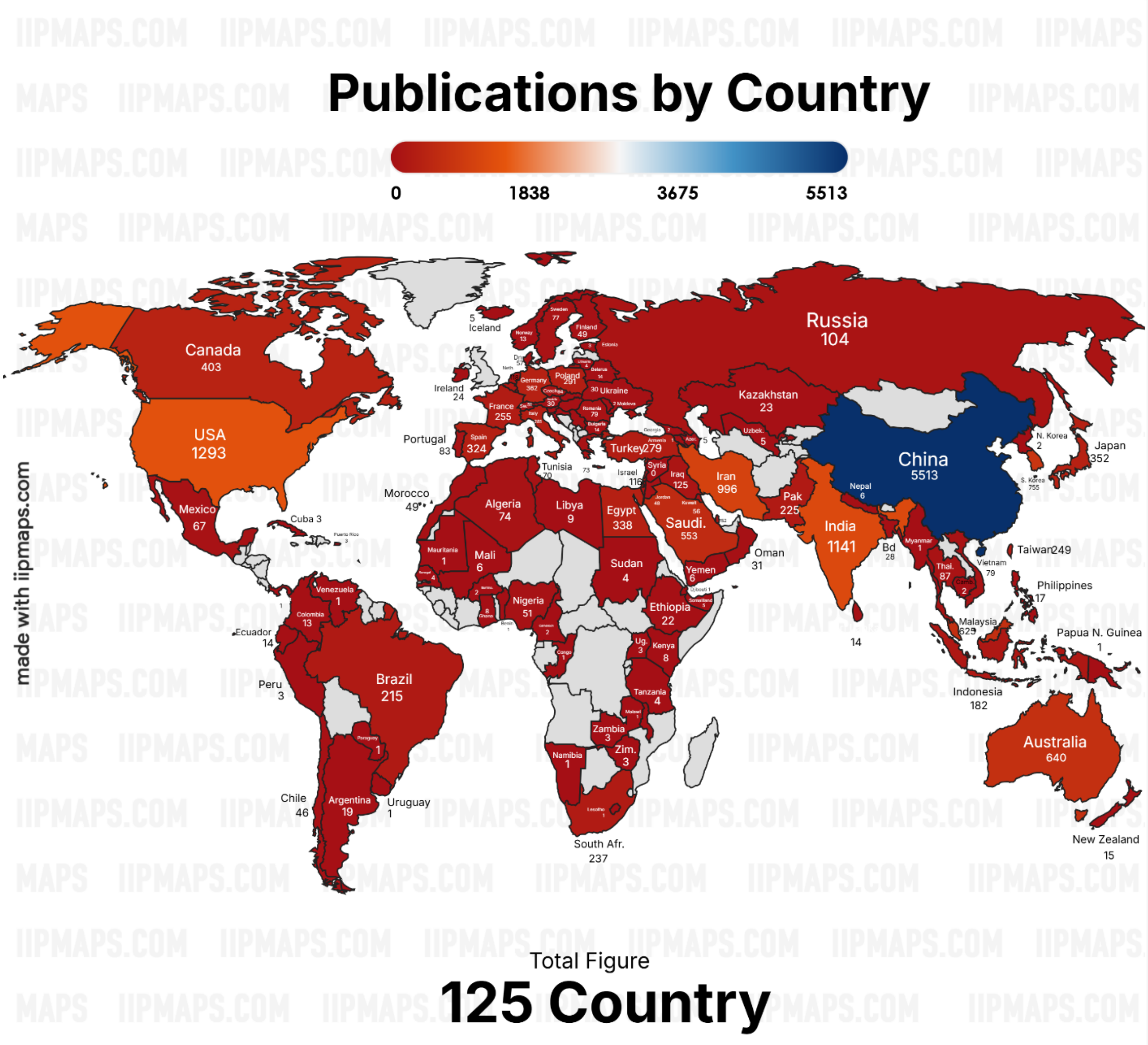

Figure 2. Summarize the publications by country

Keyword co-occurrence network

There are three main clusters in the co-occurrence network, as shown in Figure 3. Membrane, reverse osmosis, and ultrafiltration are the main clusters, with reverse osmosis and ultrafiltration being types of membranes that are widely used today [38]. Reverse osmosis is indicated by the blue cluster with a focus on desalination applications. Meanwhile, ultrafiltration is represented by the red cluster with a focus on applications in membrane bioreactors (MBR), extracellular polymeric substances (EPS), and oxidation processes, indicating a focus on pretreatment and membrane fouling, specifically biofouling [39,40].

The main clusters also generate smaller cluster branches, indicated by pink, green, and yellow clusters. The yellow cluster is connected to the red cluster, which discusses membrane fouling. The yellow cluster includes self-cleaning and photo-oxidation as part of the progress in membrane fouling solutions [41,42]. The pink group highlights the topics of nanoparticles, graphene, and surface modification, signalling a shift towards nanocomposite membranes to improve hydrophilic properties and antifouling performance [43,44]. In addition to nanoparticles, the trends of nanofibres and cellulose are also indicated by the green cluster [45]. In conclusion, this pattern indicates a shift in membrane development from mechanical enhancement to specific functional design for sustainable applications. This is evidenced by the development of conventional polymer membranes into various engineered membranes using nanomaterials.

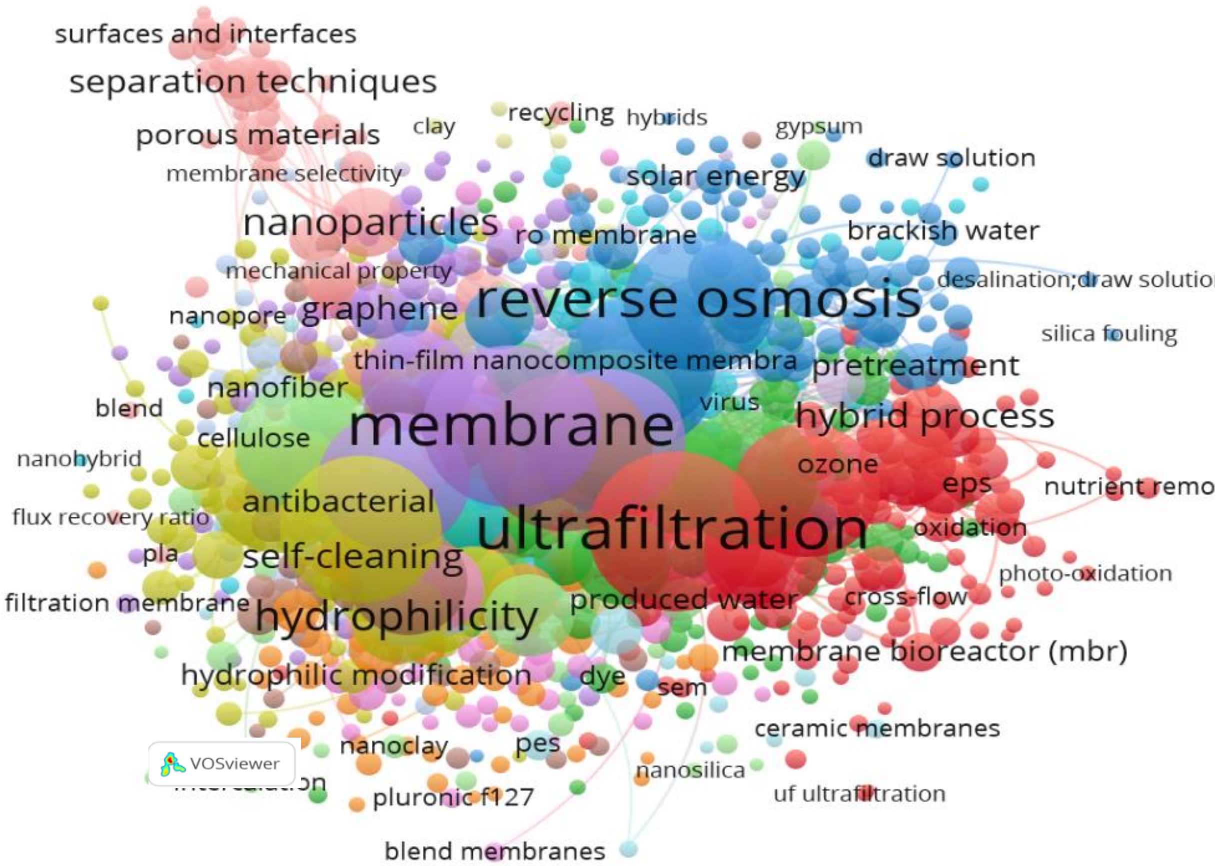

Figure 3. Visualization map of keywords (co-occurrence network) in membrane research based on Scopus data (1990–2025) using VOSviewer with a threshold of nine occurrences and association strength clustering method

Thematic evolution and knowledge transition

Various trends in membrane research from 1990 to 2025 are shown in Figure 4. The results of these three periods show the direction of research from process efficiency towards sustainable membrane applications [46,47] with the following details: (i) the initial period (1990-2005) was dominated by polymer membranes, both single and combined polymers, (ii) the transition period (2006-2015) was marked by an increase in nanocomposite membranes, and (iii) the modern period focused on the development of membranes with two-dimensional materials and multifunctional interface designs.

The terms reverse osmosis and ultrafiltration, as types of membranes, appeared most frequently in the early 1990s to 2005 (Figure 4(a)). Nanofiltration and microfiltration also appeared, but less frequently. The development of membranes has not yet seen rapid growth, with the emergence of terms related to membranes still being limited. Research focus during this period was on improving the permeability, selectivity, and fouling of polymer membranes, such as cellulose acetate membranes and extracellular polymeric substrates [48,49]. This was supported by the emergence of terms such as pore structure, operating pressure, and fluid flow characteristics. Performance improvement of membranes through optimisation of fabrication and performance parameters is crucial for the development of membranes in the next phase.

During the transition period between 2006 and 2015 (Figure 4 (b)), there was a significant increase in hydrophilic properties, permeation flux, and fouling resistance [50,51]. This was influenced by developments in nanotechnology. Terms such as silica and graphene have emerged in this phase, albeit with low intensity. In addition, various membrane production techniques that help modify membrane properties, such as electrospinning and phase inversion, have also begun to emerge significantly [52,53]. Surface engineering shows membrane advances in this phase. Active functions such as self-cleaning and antimicrobial capabilities are significant advances in this phase [46].

The use of two-dimensional materials grew rapidly during the period 2016–2025 (Figure 4 (c)). This era can be categorised as a hybrid functional era with rapid use of GO, MXene, and Janus membranes. Various terms related to membrane research have increased significantly compared to the 1990–2005 era. The use of nanomaterials has made membrane modification more active and multifunctional. This is marked by the emergence of nanofiltration in large quantities, which has high selectivity with smaller pores but optimal flux [54,55]. In addition, membrane research has also developed and focused on saving the environment through the use of green solvents, biomass sources, and eco-friendly synthesis methods [56–58].

The development of membranes in these three phases shows positive progress. Membrane fouling remains a problem in every phase. However, this problem can be reduced as membrane research progresses. The application of membranes to solve problems in everyday life is becoming more realistic with interface modifications, surface energy control, wettability regulation, and the incorporation of nanomaterials into membrane integration.

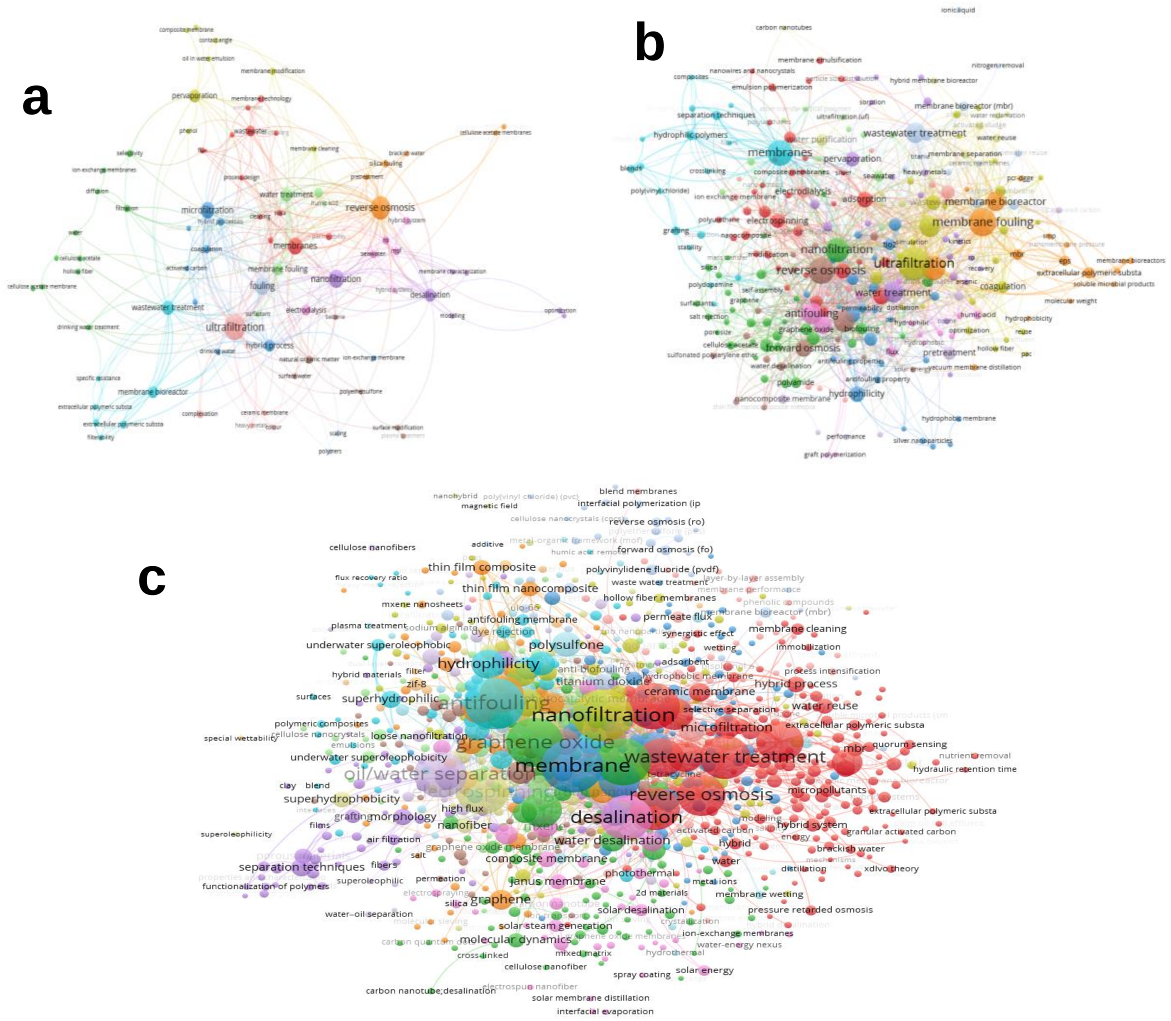

Figure 4. Thematic evolution of membrane research visualized using VOSviewer (a) period 1990-2005; (b) period 2006-2015, and (c) period 2016-2025

Emerging trends and future direction

Data mapping for the latest research was taken from data keywords of the last five years (2020-2025). The results of the latest research show a shift from single-parameter optimisation towards multifunctional membranes for membrane applications [27,47]. This is also marked by the evolution of membranes, moving from the use of polymer membranes to more varied ones with the use of nanomaterials in the manufacture of polymer membranes, such as graphene, MXene, quantum dots, TiO_2, and metal-organic frameworks (MOFs).

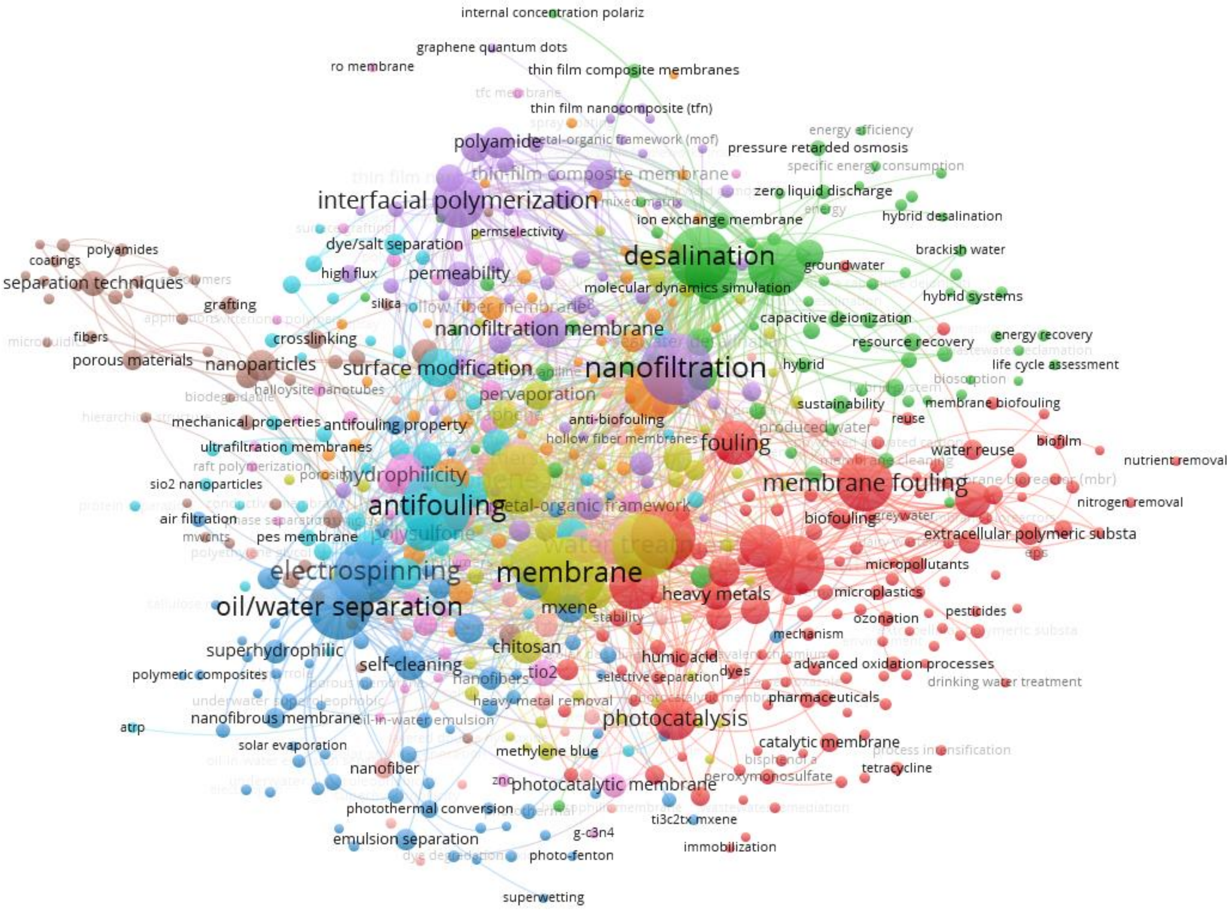

Figure 5. Visualization map of keywords in membrane research based on Scopus data (2020–2025) using VOSviewer

The results of VOS viewer mapping for the last five years of data (Figure 5) show five main clusters. The yellow cluster shows membranes as the main focus, with nanofiltration as the type of membrane that is widely developed in the purple cluster [59,60]. These two clusters show the integration of polymer membranes with nanofillers through the emergence of thin-film nanocomposites and surface modification. The main problem with membranes, since the early stages, still appears in the large node, namely membrane fouling in the red cluster [61,62]. However, the relationships within this cluster not only show the existing problems but also point to solutions used to overcome fouling problems with the emergence of photocatalysis and micropollutant removal. The focus on overcoming membrane fouling problems is also highlighted by the emergence of a large node called antifouling in the blue cluster. This cluster shows the trend of increasing research into nanostructure-oriented fabrication methods, such as electrospinning and interfacial polymerisation, to produce porous membranes with high flux and better fouling resistance [63].

This research trend is supported by several studies on membranes based on two-dimensional nanomaterials. In their research, Tu et al. fabricated a membrane from graphene and polydimethylsiloxane (PDMS) that functions to create a membrane layer similar to that of a lotus leaf, incorporating the added property of corrosion resistance [64]. In addition to graphene, graphene oxide is more widely used in membrane manufacturing applications for wastewater treatment. These applications include cleaning water from blue dye [65], oil [66], microplastics

[67], and mercury [68]. A relatively new nanomaterial used in membrane development is Mxene, which appeared in 2011. Mxene nanosheets can be used to modify hollow fibre nanofiltration membranes in their function to remove polyfluoroalkyl substances (PFAS) from water [60]. In photocatalysis, TiO_2 and Zn are widely used to accelerate the process and provide optimal results [69,70].

In addition to the use of nanomaterials in membranes, another topic that is currently attracting attention is life cycle assessment (LCA). This has led many researchers to develop research based on environmentally safe materials. Thus, the solutions provided by membranes to overcome problems do not cause other problems in other sectors. Green polymeric membranes are an effort to achieve environmentally friendly membranes [71]. This is supported by the existence of green synthesis for membrane fabrication. Green solvents such as cyrene, tamisolve, ionic liquids (Ols), deep eutectic solvents (DESs), and plant-derived oils can support green membranes [72]. Green nanoparticles also play a supporting role in membrane fabrication. The production of GO using the electrochemical exfoliation method has helped to produce green nanoparticles due to a significant reduction in the amount of chemicals used in the production process [73]. In addition, creating membranes with a longer service life and reactivating end-of-life (EOL) membranes can also help reduce the membrane production process [26].

Future research directions may lead to smart membranes that can be adjusted to respond to environmental changes, such as pH or salinity, through self-cleaning or stimuli-responsive mechanisms, which is a strategic direction in facing the needs of future water treatment systems. The development of artificial intelligence can assist in controlling this process [67]. In addition, the use of photocatalysts that assist in self-cleaning membranes can be integrated into smart membranes [50]. The process of manufacturing smart membranes can also be simplified by using molecular dynamics simulation. This can lead to the development of membranes that not only improve membrane properties but also integrate membranes with various existing advances, such as machine learning. In addition, the manufacture of membranes that take LCA into account must be a shared priority in order to maintain sustainability.

CONCLUSION

The results of research using a bibliometric approach show rapid development in membrane research in 2015. Research growth occurred rapidly in Asia. There were significant differences in the three phases of membrane development, namely the initial phase (1990-2005), the transition phase (2006-2015), and the hybrid functional membrane phase (2016-2025). These three phases show the development of polymer membranes towards integrated nanomaterial membranes with multifunctional membranes. The direction of research is not only about improving membrane properties but also includes improving sustainable performance. The future direction is expected to produce more adaptive membranes with the integration of various nanomaterials and artificial intelligence so that they can be applied to broader functions. In addition, the manufacture of environmentally safe membranes also needs to be a focus and innovation in future research.

DECLARATION OF INTEREST

There is no conflict of interest with this study.

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