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Review Paper

Unveiling Global Research Dynamics in Dynamic Membrane Bioreactor Technology: Progress, Hotspots, and Perspectives

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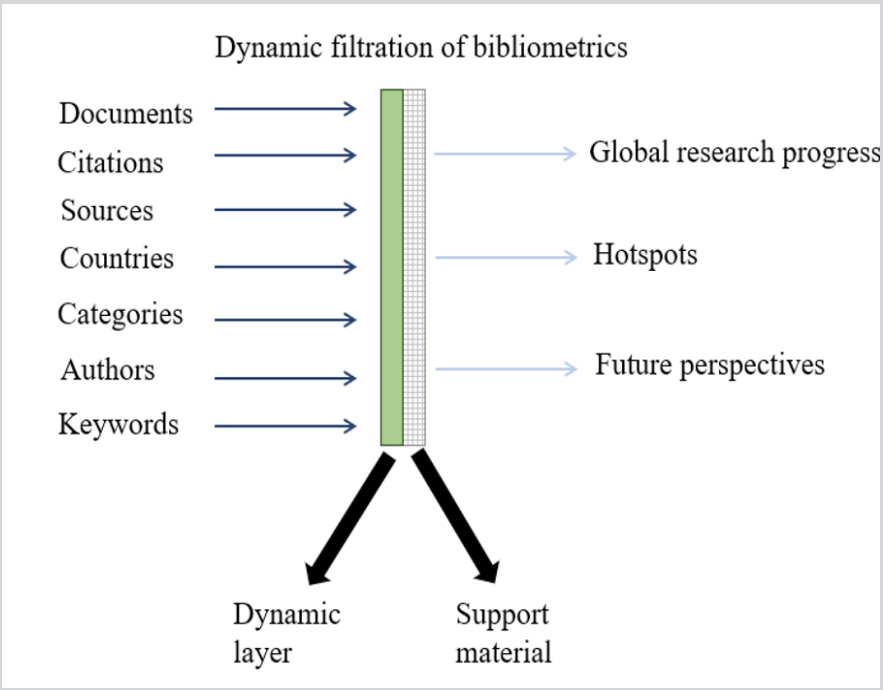
Keywords

Bibliometric analysis
Dynamic membrane bioreactor
Keyword visualization
Wastewater treatment
Membrane

Highlights

- 191 publications related to DMBR technology in the WoS database were analyzed.
- Bibliometrix and VOSviewer were utilized to visualize research advancements.
- China made the most significant contribution to DMBR research.
- The current hotspots in DMBR research were briefly reviewed.
- Future research directions were outlined to fill the gaps.

Graphical abstract



Abstract

Dynamic membrane bioreactor (DMBR) technology has emerged as a sustainable and cost-effective alternative for wastewater treatment. With its innovative approach, DMBR technology addresses global environmental challenges. This study employs bibliometric analysis to explore the development trajectory, subject categories, research trends, and international contributions in the field of DMBR technology. Using data from the Web of Science Core Collection, 206191 publications from 2000 to 20254 were analyzed with the help of Bibliometrix and VOSviewer visualization software. The findings indicate a consistent increase in annual publications, reflecting the progressive expansion and intensification of research efforts in this domain. China has emerged as the leading contributor to DMBR research, excelling in publication volume, total citations, and international collaborations. Prominent journals such as Bioresource Technology, Chemical Engineering Journal, and Separation and Purification Technology serve as key platforms for publishing research on DMBR technology. The keyword co-occurrence analysis illustrates the interrelation of research topics, revealing that advancements in DMBR research can be categorized into three distinct thematic clusters. Additionally, overlay keyword co-occurrence analysis provides a temporal perspective on emerging research trends, effectively identifying hotspots in ongoing research. Finally, future directions identified through keyword analysis are outlined to provide insights into the technology development landscape and research needs, aiming to enhance the competitiveness of DMBR technology in sustainable wastewater treatment.

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1. Introduction

The global production of wastewater has increased significantly due to population growth, urbanization, and industrialization, creating substantial pressure on existing treatment infrastructures. Untreated or poorly treated wastewater can lead to severe environmental pollution, endangering aquatic ecosystems, public health, and water security [1]. As a result, there is a growing demand for effective wastewater treatment technologies, which has driven the development and adoption of advanced systems that ensure high-quality effluent suitable for reuse or safe discharge [2,3].

Membrane bioreactors (MBRs) have emerged as a ground-breaking technology that combines biological treatment with membrane filtration to achieve superior pollutant removal efficiency. In MBRs, settling tanks are replaced with a membrane module, enabling physical filtration that effectively retains suspended solids (SS) due to the small pore sizes of microfiltration (MF) and ultrafiltration (UF) membranes [4]. This integration results in a smaller footprint, higher biomass concentration, and enhanced removal of organic matter and pathogens. Additionally, MBRs can operate at low hydraulic retention times (HRT) and high sludge retention times (SRT), offering a compact system design and greater operational flexibility compared to conventional activated sludge processes [5,6]. Despite the many advantages of MBR technology, its widespread adoption is limited by several technical and economic challenges. Conventional MBR systems often involve high capital costs associated with membrane materials, energy-intensive maintenance, and particularly the issue of membrane fouling. Membrane fouling occurs when foulants accumulate on the membrane surface or within its pores, which collectively hinder broader application, especially in resource-constrained regions [7]. This fouling not only reduces system performance but also increases operational costs due to the need for frequent cleaning and flux recovery procedures [8,9]. Such procedures typically involve substantial chemical consumption, adding to the economic burden [10]. Moreover, concerns regarding the long-term stability and durability of membranes under continuous operational conditions remain critical, underscoring the need for ongoing innovations in materials and comprehensive performance assessments [11,12]. These limitations have spurred considerable research interest in developing novel filter materials and system designs aimed at enhancing the efficiency, cost-effectiveness, and sustainability of MBR technologies.

Dynamic membrane bioreactors (DMBRs) are emerging as a promising alternative to conventional MBRs. These systems use inexpensive support materials that have large pore sizes, ranging from 10 µm to 2 mm [13]. In DMBRs, a self-forming dynamic layer—known as a dynamic membrane (DM)—develops in situ by accumulating suspended solids on a porous support material (such as nylon mesh or filter cloth) during operation. This dynamic layer serves as the primary filtration barrier [13,14,15]. This innovative approach addresses several limitations of conventional MBRs, particularly those related to filtration costs, membrane fouling, and cleaning. For instance, Ersahin et al. [16] reported that the filter cost of a DMBR was €0.04 per m^3 of permeate at a flux of 10 L/m^2h, assuming a filter cloth lifetime of four years. In contrast, Lo et al. [17] noted that the filter cost of a conventional MBR exceeded \$0.32 per m^3 of permeate at the same flux, with a membrane lifetime of five years. Another significant advantage of DMBRs is their ability to lower operational costs associated with membrane fouling, a common issue in standard MBRs. The dynamic layer in DMBRs can be renewed and is often less prone to fouling compared to conventional membranes. Consequently, this leads to less frequent cleaning and reduced energy demands [18]. Additionally, fouled membranes can be easily cleaned using physical methods, such as filter flushing, eliminating the need for chemical cleaning and the associated costs [19]. Previous comparative studies have shown that the treatment and filtration performance of DMBRs can rival that of conventional MBRs once a homogeneous DMis established on the support material under the same operating conditions [20,21]. Furthermore, DMBRs have demonstrated the potential for long-term stable operation, reinforcing their competitiveness in wastewater treatment [5]. In this context, the innovative DMBR technology is gaining increasing attention as a cost-effective alternative for wastewater treatment.

Over the past two decades, only a limited number of comprehensive reviews have explored DMBR technology from multiple perspectives, assessing its effectiveness and reliability across various applications. These studies have examined key factors such as the formation of DM, the influence of support material types on filtration performance, and specific fouling mitigation and cleaning strategies for DMBR systems [13,15,18]. Additionally, several review papers have focused on the applicability of anaerobic DMBR (AnDMBR) configurations for energy recovery from wastewater, highlighting their potential as cost-effective filtration solutions [19,22]. However, existing reviews lack a comprehensive and up-to-date analysis that reflects the most recent advancements and emerging trends in DMBR research. Furthermore, many of these studies do not adequately examine collaborative research networks or the complex interrelationships among various research themes within the field. In recent years, bibliometric analysis has become a widely used method for examining, understanding, and generating indicators that reflect the development and dynamics of scientific knowledge in specific research areas [23]. This technique involves analysing quantitative aspects of scholarly outputs, such as articles, books, patents, and references, including citations and co-citations. By using statistical and mathematical techniques, it uncovers patterns related to specific subjects. Bibliometric analysis evaluates the research productivity of individuals, institutions, or nations within a particular field, providing valuable insights into the current state of research and helping researchers identify potential new directions for future studies [24].

While bibliometric analyses have been conducted on membrane-based treatment technologies, including membrane distillation [25], forward osmosis [26], and membrane photobioreactors [27], no bibliometric analysis has yet been performed specifically for DMBR technology. Therefore, an in-depth investigation into technological advancements, emerging trends, and existing research gaps within the DMBR literature is warranted.

This study provides a comprehensive overview of DMBR technology through bibliometric analysis for the first time. The aim of the study is to quantitatively and qualitatively evaluate related publications using data from the Web of Science (WoS) database. By incorporating recent information, this study seeks to present an up-to-date overview of the evolving landscape of DMBR research. The analysis focuses on the overall research output in this field, highlighting key journals, subject categories, as well as the contributions from different countries and researchers. Additionally, it identifies commonly used keywords, research hotspots, and emerging trends that may influence the future direction of DMBR studies. This complete approach not only traces the historical development of the field but also reveals current trajectories and potential research avenues. The insights gained from this analysis are intended to provide valuable perspectives on the current state of DMBR research and to serve as a foundation for guiding future investigations and technological advancements in this critical area.

2. Materials and methods

2.1. Data source and data retrieval

The WoS Core Collection database was selected for data collection due to its longstanding reputation as one of the most comprehensive sources of citation data globally [28]. The WoS Core Collection includes several citation indices, such as the Science Citation Index Expanded, the Conference Proceedings Citation Index - Science, the Book Citation Index - Science, the Emerging Sources Citation Index, and the Social Sciences Citation Index. The research query utilized the keywords "dynamic membrane bioreactor" and "mesh filtration" without applying any specific time frame. The term "mesh filtration" was included based on its usage by some authors in their publications, particularly during the early years of DMBR, when there had not yet been a consensus on terminology. To minimize any potential bias from continuous updates to the database, the search for relevant papers was conducted once in February 2026. Additionally, the search was restricted to articles and reviews published in English. Initially, this research yielded a total of 1,510 articles in the database. However, it is commonly recognized that many of these articles may not be directly related to the topic [29,30]. Consequently, each data record (including the title and abstract) was meticulously reviewed and screened to eliminate irrelevant information. After this pre-screening process, 206 article records were deemed sufficiently relevant. Basic statistical data, including the number and growth of publications categorized by year, journal, and country, as well as research categories, subject areas, and keywords, were exported in .ris, .bib, and .xlsx formats for further analysis.

2.2. Methodology

Bibliometric tools are effective methodologies that apply mathematical analysis and statistical techniques to quantitatively examine the distribution, evolution, and relationships among academic documents. This approach helps uncover research trends across various fields of study [29]. For this analysis, we utilized Bibliometrix software (version 4.4.2) based on R-language [31] and VOSviewer software (version 1.6.20) [32] as bibliometric tools. Bibliometrix was used to analyze the number of publications and citations, examine authorship, and assess countries, sources, and research categories. It also allowed us to apply Lotka's Law and generate thematic keyword maps. In contrast, VOSviewer was employed for keyword co-occurrence analysis and overlay visualizations. Additionally, some bibliometric data were exported in .xlsx format from Bibliometrix for further use in Microsoft Excel 2016, where we created graphical representations. The main steps of data retrieval and bibliometric analysis are illustrated in Fig. 1.

The h-index is a widely recognized metric used to evaluate an individual's scientific contributions. It is defined as the number of papers (h) that have been cited at least h times, reflecting both productivity and citation impact. The m-index is derived by dividing the h-index by the number of years since the author's first publication (m = h-index/n, where n represents the number of years). This offers an indicator that is adjusted for the length of the author's career. The g-index prioritizes highly cited works by assigning more weight to the most frequently cited papers in a dataset. This approach accounts for the changing citation impact of influential publications over time [33]. These indices can be automatically calculated using Bibliometrix software.

Lotka's law describes the relationship between authors and their publication frequency, serving as a valuable indicator of scientific productivity. According to this law, the proportion of researchers with n publications is inversely proportional to the square of n (i.e., $1/n^2$). This provides a mathematical framework for understanding how contributions to scientific literature are distributed among authors. Lotka's law is defined as follows [34]:

$$Y = \frac{C}{X^n} \quad (1)$$

Where, X represents the number of publications; Y denotes the frequency of authors with X publications, and C and n are constants estimated using the Bibliometrix software within the specified domain.

Various simulation approaches have been developed to forecast technological advancements. Since technologies often progress along an S-curve trajectory, many researchers have utilized this model to simulate development stages and assess the level of technological maturity [24,27,35]. The Logistic model has been employed for S-curve simulation to quantitatively evaluate the potential development of technology, using Loglet Lab 4 software. The S-curve can be expressed using the following equation:

$$Y_t = \frac{K}{1+e^{-a(t-b)}} \quad (2)$$

where, Y_t denotes the dependent variable for the S-curve, representing the cumulative number of annual publications. The variable t signifies time for the S-curve, while a and b are model parameters, and K refers to the "publication ceiling value" considered in this study [35].

3. Results and discussion

3.1. Publication outputs

This study retrieved 206 articles on DMBR technology published between 2000 and 2025 from the WoS database after going through multiple pre-processing stages. Table 1 presents key information from the collected data for analysis. The findings indicate that 659 authors from 27 countries have contributed to this field, with 542 keywords derived from these authors. Notably, there were no single-authored documents in the dataset. Each document was published with an average of 5.96 co-authors, and the international co-authorship ratio stands at 26.2%, suggesting a moderate level of collaboration among authors and countries. The documents have an average age of 5.96 years and a total of 6,033 citations, resulting in an average of 30.28 citations per document. The h-index for DMBR research is 45, which reflects significant scholarly contributions and citation impact, highlighting the increasing relevance and dynamic nature of research in this field.

Fig. 2a demonstrates the growing trend of annual and cumulative publications of DMBR studies, as well as annual citation counts. The findings reveal a steady upward trajectory in research on DMBR from 2000 to 2025, with an average annual growth rate of 12.44%. Based on the cumulative growth of publications, it is evident that there has been a remarkable increase in the number of publications since 2012. Therefore, research development stages can be evaluated in two different time intervals: (1) The initial stage (2000-2012): During the early stage of research, only a limited group of scholars participated, leading to a relatively modest publication count of just 21 articles, making up 11% of the total published papers. (2) Maturation stage (2012-2025): Following the recognition of the subject's innovative aspects and the need for further exploration, there has been a substantial increase in papers with the participation of more scholars in research activities. During this period, 185 studies were published, accounting for 90% of the total publications. Concurrently, the annual number of citations has generally increased steadily, except for certain fluctuations. This upward trajectory highlights the growing importance and impact of DMBR research, reflecting the scientific community's acknowledgment of progress, novelty, and contributions within the scientific discourse of the field. Given the observed trends in publications and citations, this field is likely to continue progressing rapidly in the coming years.

Table 1
Main statistics of DMBR literature.

Description	Results
Timespan	2000-2025
Documents	206
Sources	56
Citations	6,033
Documents average age	5.92
Author's keywords	542
Author	659
Co-author per document	5.96
International co-authorship (%)	26.2
Contributed countries	27
H-index	45

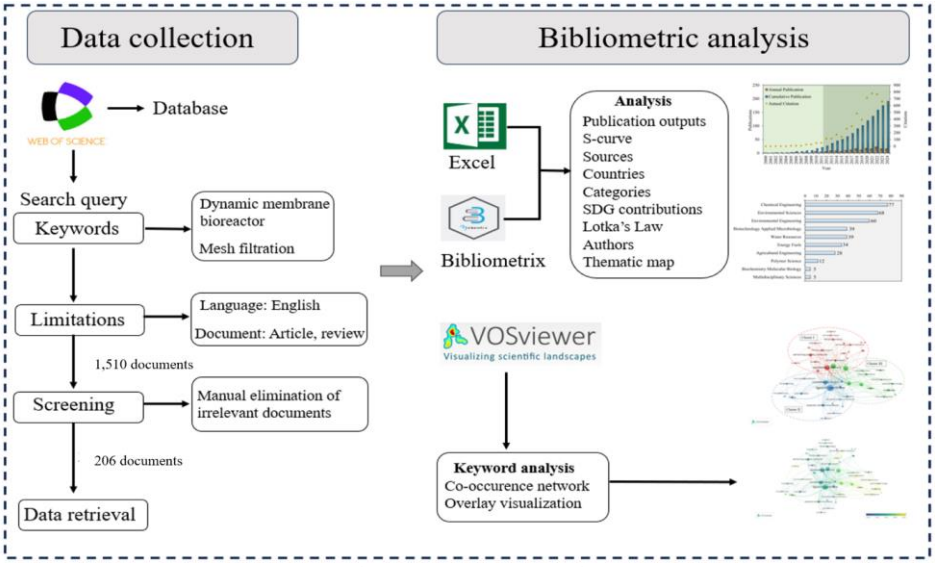


Fig. 1. Data collection flowchart and methodology of bibliometric analysis.

The S-curve growth model is a statistical tool used to predict and analyse the dynamics of scientific output within a specific research field [36]. The S-curve derived from the data shows that the research field has moved from the emergence phase into the development and maturation phases (Fig. 2b). This indicates that the progress of research on DMBR technology has considerable time left before it reaches the declining stage, suggesting there is still significant potential for further innovation and development.

3.2. Sources and most relevant research fields

The distribution of journals provides valuable insights into the concentration and impact of published literature, serving as a key metric for assessing the developmental stage of a research field [37]. An analysis of the WoS database reveals that research on DMBR is published across 56 journals. Notably, the top ten journals account for 64.71% of all publications and 76.24% of total citations, indicating a significant concentration of influential work in a few key outlets, as seen in Table 2.

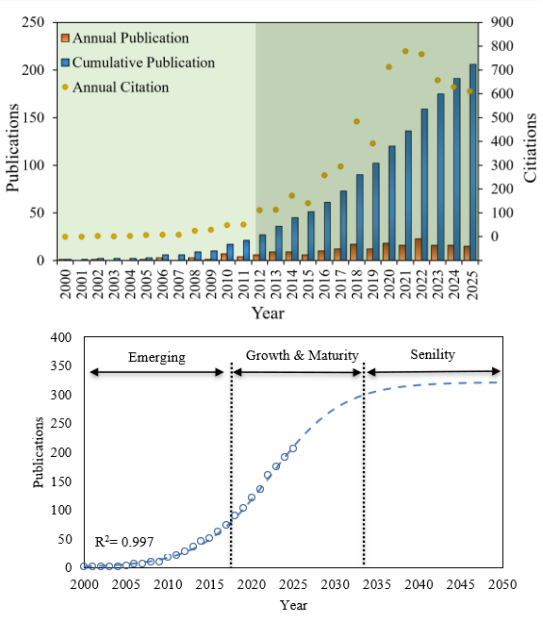


Fig. 2. (a) The growth of publications and citation numbers, (b) The S-curve analysis.

The analysis of research categories automatically generated by the WoS serves as a valuable tool for identifying and examining disciplinary trends within the field. Fig. 3 shows the top ten WoS categories and their contributions to the United Nations' Sustainable Development Goals (SDGs). According to WoS categorization, studies related to DMBR technology were associated with 24 distinct categories. The most significant categories include Chemical Engineering (40.78%), Environmental Sciences (35.44%), Environmental Engineering (31.55%), Biotechnology and Applied Microbiology (20.39%), and Water Resources (19.42%) (Fig. 3a). This distribution indicates that DMBR research encompasses multiple domains, underscoring its multidisciplinary and interdisciplinary nature.

Table 2
Leading the top 10 sources for DMBR technology.

Source	N. of publication	h-index	Total citation	Impact factor (Quartile)
Bioresource Technology	28	20	1,321	9.0 (Q1)
Chemical Engineering Journal	24	13	799	13.2 (Q1)
Separation and Purification Technology	12	11	532	9.0 (Q1)
Journal of Membrane Science	11	9	504	9.0 (Q1)
Water Research	11	8	765	12.4 (Q1)
Journal of Environmental Management	10	7	192	8.4 (Q1)
Science of the Total Environment	9	7	268	-
Desalination and Water Treatment	9	6	76	1.0 (Q4)
Chemosphere	4	4	144	-
Water Science and Technology	4	4	53	2.6 (Q2)

Both Chemical Engineering and Environmental Engineering have shown significant interest in DMBR research, positioning these fields at the forefront of engineering innovation. DMBR technology has made considerable contributions to areas such as Environmental Sciences, Applied Biotechnology, and Water Resources. This is primarily due to its effectiveness in wastewater treatment, its role in reducing environmental pollution, its impact on water resource conservation, and its potential as a key biotechnology solution. Research on the Sustainable Development Goals (SDGs) has gained significant momentum across various academic disciplines, as scholars aim to address pressing global challenges [38]. According to the WoS categorization, 204 out of 206 publications were linked to at least one of the SDGs (Fig. 3b). Unsurprisingly, SDG 6 (Clean Water and Sanitation) was the most represented, with 201 publications. Additionally, 39 publications were associated with SDG 7 (Affordable and Clean Energy), highlighting the interest in energy recovery through DMBR technology in wastewater treatment. Furthermore, 34 publications were linked to SDG 12 (Responsible Consumption and Production), illustrating the role of DMBR technology in wastewater management and the preservation of water resources.

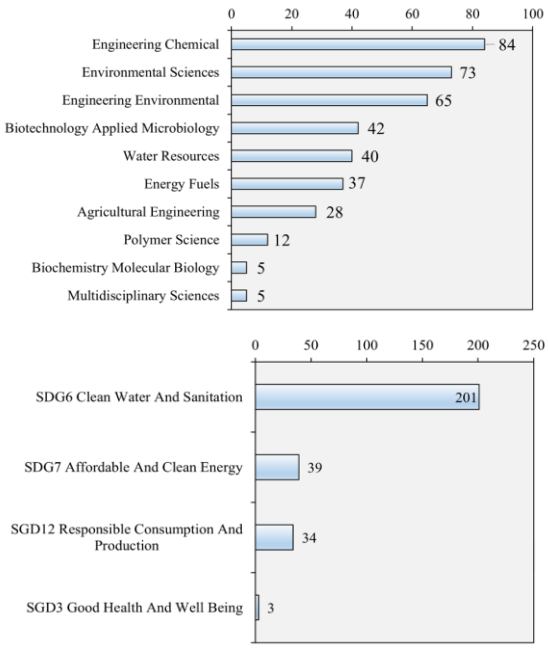


Fig. 3. (a) Top ten WoS categories, (b) contribution of documents to SDGs.

3.3. Leading countries, global collaboration patterns

Research on DMBR technology in wastewater treatment has received contributions from 27 countries worldwide, reflecting its global significance. Fig. 4a presents the frequency of countries affiliated with authors in the dataset on a world map, along with statistics for the top five leading countries. China has made a significant contribution to this research field, with 121 documents published, accounting for 61.12% of the total publications, followed by South Korea (22, 11.12%), Turkiye (21, 10.88%), Italy (16, 8.21%), and the USA (11, 5.38%). This prominence may be linked to their extensive research infrastructure, robust funding opportunities, and the significant emphasis placed on environmental science and technology advancements. Specifically, the Chinese government's "Twelfth Five-Year Plan" (2011–2015), introduced in 2010, prioritized addressing water pollution challenges, potentially driving the growth of academic publications in this field within China. Furthermore, the 2015 "Action Plan for Prevention and Control of Water Pollution" (commonly known as "Water Ten"), which aimed to reduce pollution from various industries, significantly contributed to enhancing academic research output by fostering innovation and a focus on environmental solutions [35]. South Korea's Water Vision 2020, published in 2000, outlines a comprehensive approach to water resource management aimed at addressing water pollution, improving water quality, and ensuring sustainable water use, leading to creating more academic effort on sustainable water treatment technologies in the country [39]. Turkiye, as a candidate country for the European Union (EU), and Italy, as an EU member state, have adopted the European Water Framework Directive (2009) and the European Green Deal (2022), which propose stringent regulations to reduce pollutants in surface and groundwater. These regulations focus on sustainability and encourage innovations in wastewater management,

particularly by promoting technologies that address water quality and pollution control across Europe [40]. The Clean Water Act (CWA), passed in 1972, is a pivotal environmental legislation in the United States designed to mitigate water pollution and preserve the quality of the nation's water resources. To support this, the U.S. government allocated over 1 billion USD to combat water pollution, fostering the development of innovative, eco-friendly technologies to improve water quality [41].

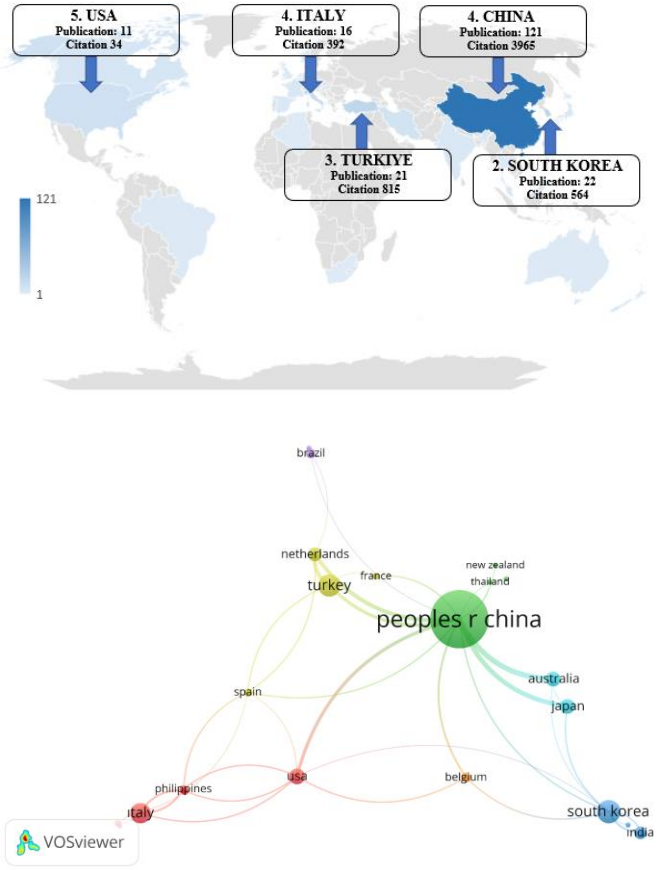


Fig. 4. (a) Most productive countries, (b) international collaboration relationships among countries.

Fig. 4b illustrates the collaboration between countries in publications using social network analysis. Each circle represents a country, with its size indicating the number of publications attributed to that country. The connecting lines between circles signify collaborative relationships, where thicker lines indicate stronger or more frequent cooperation between the respective countries. The analysis reveals the most significant collaborative relationship between China and Australia, with eight joint efforts. Additionally, the second-highest level of collaboration is observed between China and Japan, with seven shared publications. Subsequently, China and the Netherlands, as well as Turkiye and the Netherlands, recorded the third-highest levels of international collaborations, with six partnerships each.

3.4. Prolific authors and most cited articles

The application of bibliometric analysis to assess an author's productivity is an effective tool for identifying the most influential contributors within a specific research domain. In this context, plotting Lotka's Law provides valuable insights into the frequency and distribution of authors contributing to research on DMBR, offering a detailed examination of authorship trends in the field [42].

Fig. 5 shows the author productivity determination by Lotka's Law. The analysis indicates that 68.8% of authors have contributed only a single article, 14.9% have published two articles, and 6.1% have authored three articles. As the number of publications increases, the proportion of contributing authors declines; only 1.3% of researchers have produced more than 10 articles. This distribution aligns with Lotka's Law, suggesting that a smaller subset of dedicated researchers is responsible for repeated contributions to DMBR research. Simultaneously, a significant proportion of authors contribute without consistent continuity.

Table 3 presents the ten most prolific authors in the field, detailing their total number of publications, corresponding indices, total citations, and the year their publication activity began. HU Y., KIM S.H., and WANG X.C. rank as the top three most prolific authors, having published 15, 14, and 13 articles, respectively (WANG X.C. and WANG Z. share third place with the same number of publications). In terms of total citations, WANG Z. ranks first with 828 citations, followed by OZGUN H. and ERSAHIN M.E., who are tied for second place with 721 citations each. Wang X.C. holds the third position with 555 citations.

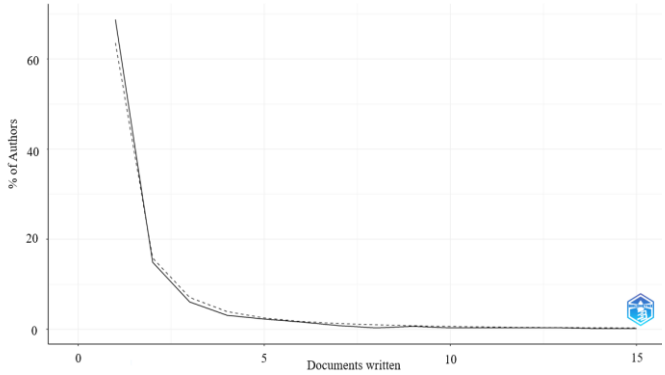


Fig.5. Author productivity determination by Lotka's Law.

Highly cited articles serve as a crucial indicator in a research field, showcasing the most influential, studied, and developed topics related to the area of interest [43]. Table 4 presents the top 10 most cited publications in the field of DMBR research. The review articles hold the 1st (323 citations) and 9th (115 citations) positions on this list, while the remaining highly cited works are original research articles. The second-ranked article (225 citations) investigates how progressively increasing organic loading rates (OLR) and total ammonium nitrogen (TAN) concentrations impact the performance of an AnDMBR system at a pilot scale. It focuses on treatment efficiency, biogas production, and microbial community dynamics in challenging landfill leachate wastewater. This wastewater is characterized by TAN levels exceeding 3 g/L and chemical oxygen demand (COD) concentrations greater than 13 g/L [44].

Table 3
The top ten most prolific authors in the field.

Author	N. of publication (rank)	h-index	g-index	m-index	Total citation (rank)	First publication year
Hu Y.	15 (1)	10	15	1.111	528 (4)	2016
Kım S.H.	14 (2)	10	14	2.000	243 (8)	2020
Wang X.C.	13 (3)	10	13	0.769	555 (3)	2016
Wang Z.	13 (3)	10	13	0.769	828 (1)	2010
Ozgun H.	12 (4)	10	12	1.667	721 (2)	2012
Ersahın M.E.	12 (4)	10	12	1.111	721 (2)	2012
Zhang Y.	12 (4)	8	12	0.667	374 (5)	2010
Parj J.H.	10 (5)	10	10	0.553	254 (6)	2019
Lıu H.	9 (6)	7	9	1.000	246 (7)	2009
Chen G.	9 (6)	7	9	0.438	189 (9)	2018

The third-ranked article (202 citations) is one of the earliest contributions in this field, examining the effect of a dacron mesh with a pore size of 100 µm on the removal of conventional pollutants, including COD, ammonium nitrogen, and suspended solids (SS), in municipal wastewater using a DM within an aerobic MBR system [45]. The fourth study on the list provides an in-depth analysis of the mechanisms underlying DM formation during municipal wastewater treatment, detailing the sequential stages involved in this process [46]. The fifth (139 citations), sixth (126 citations), and tenth (106 citations) papers can be grouped together as they all investigate the effects of various process parameters, including SRT, HRT, mixed liquor suspended solids (MLSS) concentration, and aeration regimes, on the treatment and filtration performance of both anaerobic [47] and aerobic [48,49] DMBR systems. The seventh-ranked article (124 citations) explores the treatment potential of DM for removing non-biodegradable micro-particles, such as plastics, which conventional sedimentation methods do not effectively

eliminate. It also assesses which blockage model within the Hermia framework most closely aligns with the dynamic filtration process [50]. Finally, the eighth-ranked study (116 citations) examines the impact of a gravity-driven DMBR system with varying HRT arrangements on the treatment performance of household wastewater, presenting a novel approach to wastewater management [51].

3.5. Research hotspots and frontiers

3.5.1. Analysis of keyword frequency and co-occurrence patterns

Analysing the keywords in research articles provides a clear overview of the main topics within a specific field, as these keywords reflect the central themes and scope of the studies [52].

Using VOSviewer software, we constructed a co-occurrence network of keywords to identify research hotspots in the domain. The keyword list was carefully curated prior to analysis to ensure consistency and accuracy. We applied a minimum occurrence threshold of three, resulting in a total of 52 keywords included in the visualization (Table 5), thereby enhancing the precision of the analysis. Fig. 6 illustrates the co-occurrence network clustering of keywords along with their overlay visualization. In Fig. 6a, the strength of the connection between two keywords reflects the frequency of their co-occurrence in the same publication. The size of each circle corresponds to the total occurrences of the associated keyword, with larger circles indicating more frequent usage. Additionally, the color of the circles represents the year of publication, as shown in the color-year scale in Fig. 6b. This visualization allows for an analysis of the evolution of research topics over time, highlighting historical trends and shifting research hotspots within the field. We identified three clusters of keywords related to DMBR studies. Each cluster represents a collection of central themes grouped around related keywords. The following sections will outline the conceptual frameworks and key insights associated with each cluster.

Cluster I (red) highlights the applicability of DMBR technology in wastewater treatment processes. The top three keywords are wastewater treatment (35 occurrences), self-forming dynamic membrane (14 occurrences), and cake layer (9 occurrences). This cluster emphasizes cake layer formation, filtration performance, and the resistance of the biofilm (DM layer), offering insights into the effectiveness of dynamic filtration technology, especially domestic/municipal wastewater treatment, as a central theme. Cluster II (blue) revolves around AnDMBR applications and the characteristic properties of support materials and membrane configurations, with the top three keywords being membrane bioreactor (28 occurrences), anaerobic dynamic membrane bioreactor (17 occurrences), and filtration (9 occurrences). Combining DM with anaerobic digestion has gained scholarly attention due to its advantages, including (1) energy recovery, (2) minimal sludge generation, and (3) the elimination of energy-intensive aeration requirements [53]. The related keywords mesh filtration, support material and pore size reflect research trends aimed at understanding the impact of different support materials and their pore sizes on the DM filtration process as both support material and its pore size directly affect DM formation and its filtration performance [54,55]. The keyword hollow fibre also indicates a research interest in exploring DM technology with different membrane configurations [56].

Cluster III (green) delves into the membrane fouling phenomenon in DMBR studies and microbial community dynamics in bioreactors, with the leading keywords being dynamic membrane bioreactor (34 occurrences), membrane fouling (32 occurrences), and microbial community (21 occurrences). Closely related keywords, such as anaerobic (5 occurrences), anaerobic digestion (5 occurrences), and AnDMBR (3 occurrences), highlight research efforts on AnDMBR studies and microbial community patterns. Additionally, the keywords food waste (8 occurrences) and dark fermentation (7 occurrences) demonstrate novel approaches in DMBR technology, as food waste plays a significant role in anaerobic co-digestion for biogas production and biohydrogen production during dark fermentation due to its high organic content, which makes it an excellent substrate for microbial processes.

The colour transition from green to yellow in Fig. 7b illustrates the latest keywords used in DMBR research through clustering overlay visualization. In particular, keywords covered by Cluster III, such as dark fermentation, biofilm, food waste, waste-activated sludge, and anaerobic digestion, highlight hotspots in the ongoing research progress on DMBR studies.

Table 4
The top ten most cited articles in DMBR research.

Rank	Title	Summary	Citations	Citations per year	Journal	Year	Reference
1	A review on dynamic membrane filtration: Materials, applications, and future perspectives	Reviews, as a first review article in the field, support materials characteristic properties, system configurations, and affect DM filtration performance	323	23.07	Bioresource Technology	2012	[15]
2	An anaerobic dynamic membrane bioreactor (AnDMBR) for landfill leachate treatment: Performance and microbial community identification	Presents the applicability of a pilot-scale AnDMBR system for landfill leachate treatment over long-term operation, with a focus on examining shifts in microbial communities	225	18.75	Bioresource Technology	2014	[44]
3	Characteristics of a Self-Forming Dynamic Membrane Coupled with a Bioreactor for Municipal Wastewater Treatment	Presents the biological and filtration performance of coarse mesh support material coupled with an aerobic bioreactor for municipal wastewater treatment	202	8.42	Environmental Science & Technology	2002	[45]
4	Formation of the dynamic membrane in an anaerobic membrane bioreactor for municipal wastewater treatment	Presents DM formation stages (i.e., formation, stable growth, and fouling stage) in an AnDMBR during municipal wastewater treatment	140	8.75	Chemical Engineering Journal	2010	[46]
5	Applicability of dynamic membrane technology in anaerobic membrane bioreactors	Examines the effect of SRT on biological performance and DM filtration performance during high-strength wastewater treatment	139	11.58	Water Research	2014	[47]
6	Wastewater treatment performance of a filtration bio-reactor equipped with a mesh as a filter material	Reveals the effect of operational parameters such as MLSS concentration, mesh pore size, HRT, and aeration regime on filtration and treatment performance of DMBR, as a first published paper on DMBR technology	126	4.85	Water Research	2000	[48]
7	Dynamic membrane for micro-particle removal in wastewater treatment: Performance and influencing factors	Presents the effect of applied flux on micro-particle removal performance and explores the Hermia filtration model fitting to DM filtration	124	15.50	Science of the Total Environment	2018	[50]
8	Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household wastewater treatment	Presents filtration and treatment performance of the gravity-driven DM process with a focus on the effect of HRT	116	7.25	Water Research	2010	[51]
9	Anaerobic dynamic membrane bioreactor (AnDMBR) for wastewater treatment: A review	Reviews the impact of reactor configurations, support material properties, operational conditions, sludge and wastewater characteristics on pollutant removal, DM filterability, and biogas production	115	14.38	Bioresource Technology	2018	[22]
10	Filtration capability and operational characteristics of a dynamic membrane bioreactor for municipal wastewater treatment	Presents the effect of MLSS concentration on DM formation and explores cleaning protocols on permeability recovery	109	5.45	Separation and Purification Technology	2006	[49]

This study identified 52 keywords in DMBR research through quantitative and clustering analyses. Despite the thematic richness revealed by the three clusters, their development has largely progressed in parallel rather than through an integrated framework. Cluster I predominantly focuses on cake layer formation and filtration performance, Cluster II emphasizes reactor configuration and support material characteristics in DMBR systems, while Cluster III concentrates on membrane fouling and microbial community dynamics. The limited interaction among these clusters can be attributed to differences in research focus, experimental design, and performance evaluation approaches, which often examine structural, operational, and biological aspects separately. Integrating these domains could generate substantial advancements. For instance, linking microbial community structure and EPS composition (Cluster III) with cake layer resistance and structural properties (Cluster I), while simultaneously optimizing support material pore size and configuration (Cluster II), could facilitate the rational design of DMBR systems with improved operational robustness, energy efficiency, and scalability in full-scale applications. Establishing such connections represents a key opportunity for future research. Overall, the bibliometric map suggests that research in this field is expected to grow and diversify, encompassing a broader range of keywords and topics by bridging distant and currently unrelated areas, thereby enabling novel and more application-oriented developments.

3.5.2. Analysis of thematic map visualization

Fig. 7 presents a thematic map of the authors' keywords, highlighting their relevance and level of development within various research fields. Each network cluster is represented by a bubble, with the bubble name corresponding to the term that appears most frequently within the cluster. The size of the bubble indicates the number of occurrences of words in that cluster, while its position is determined by the cluster's Callon density and centrality.

Table 5
Keywords included in the visualization.

Cluster no	Keyword (occurrences, total link strength)
1	Wastewater treatment (35,73), self-forming dynamic membrane (14,17), cake layer (9,25), domestic wastewater (7,10), filtration performance (8,15), filtration resistance (6,10), mbr (5,9), self-forming dynamic membrane bioreactor (5,6), powdered activated carbon (5,15), dynamic filtration (4,8), mesh filter (3,8), sludge property (3,11), biofilms (3,7), biofouling (3,5), cake layer formation (3,5), extracellular polymeric substances (3,5), biodegradation (3,4), mesh (3,4), nylon mesh (3,4), dynamic membrane filtration (3,3).
2	Dynamic membrane (53,108), membrane bioreactor (28,58), anaerobic dynamic membrane bioreactor (17,26), filtration (9,15), municipal wastewater (10,21), mesh filtration (8,17), fouling (7,16), hollow fibre (5,15), landfill leachate (4,10), municipal wastewater treatment (4,10), denitrification (4,9), biogas (3,7), support material (3,10), pore size (3,9), textile wastewater (3,9), café filtration (3,8), bio-diatomite dynamic membrane (3,6), nitrogen removal (3,5).
3	Dynamic membrane bioreactor (34,47), membrane fouling (33,42), microbial community (21,41), anaerobic membrane bioreactor (11,22), food waste (8,14), dark fermentation (7,8), biofilm (6,13), anaerobic (5,11), anaerobic digestion (6,9), waste activated sludge (5,10), hydraulic retention time (3,8), andmbr (3,6), bioaugmentation (3,4), trans-membrane pressure (4,4).

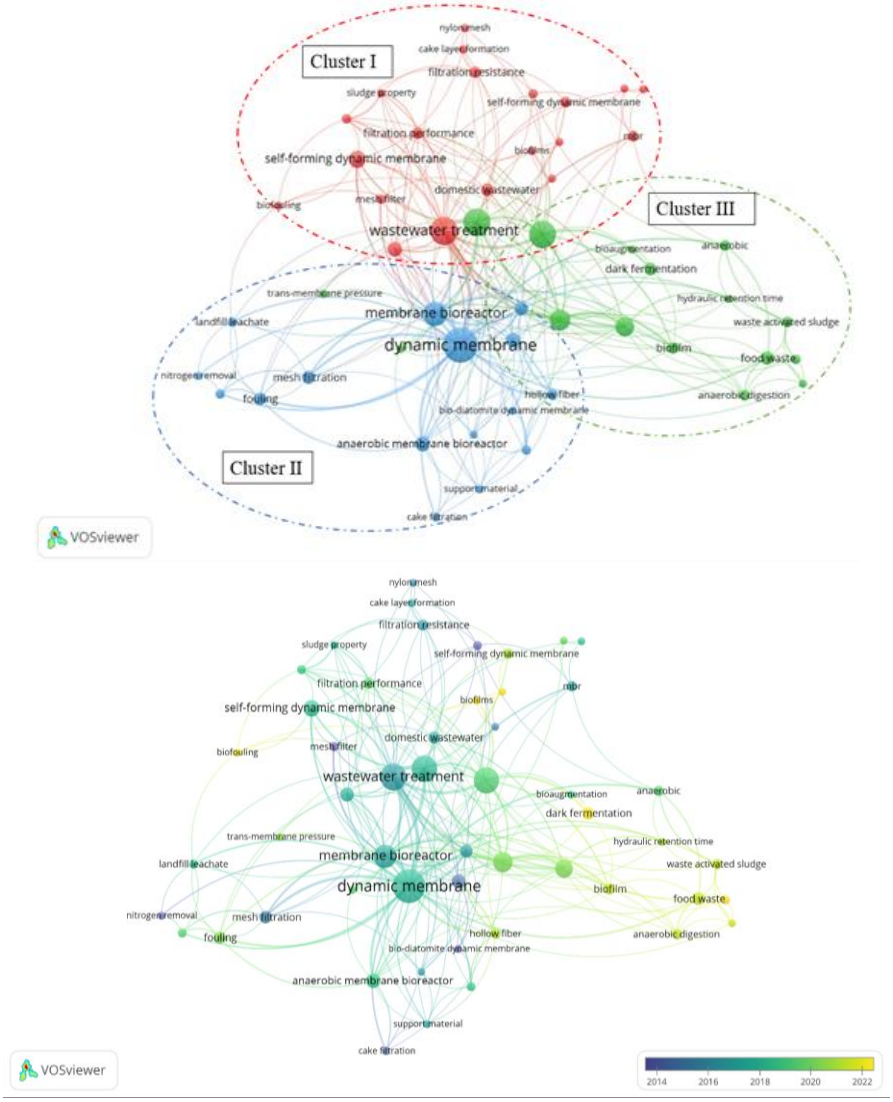


Fig. 6. (a) Co-occurrence network clustering of keywords, (b) keywords overlay visualization.

Centrality measures the degree of interaction between clusters, showing how connected a topic is to other topics. In contrast, density reflects the cohesion within a cluster, indicating how closely the terms are linked to one another. This thematic map provides a clear visualization of research themes, divided into four quadrants: (i) motor themes, (ii) basic themes, (iii) emerging or declining themes, and (iv) niche themes. Motor themes are central, well-established topics that significantly influence the field and form the foundation for related sub-themes. Basic themes represent fundamental concepts that underlie the field, serving as a basis for further exploration. Emerging themes are innovative topics that are gaining attention and may shape future research. Niche themes are specialized topics that are less prevalent in mainstream discussions but offer valuable insights for specific researchers [57].

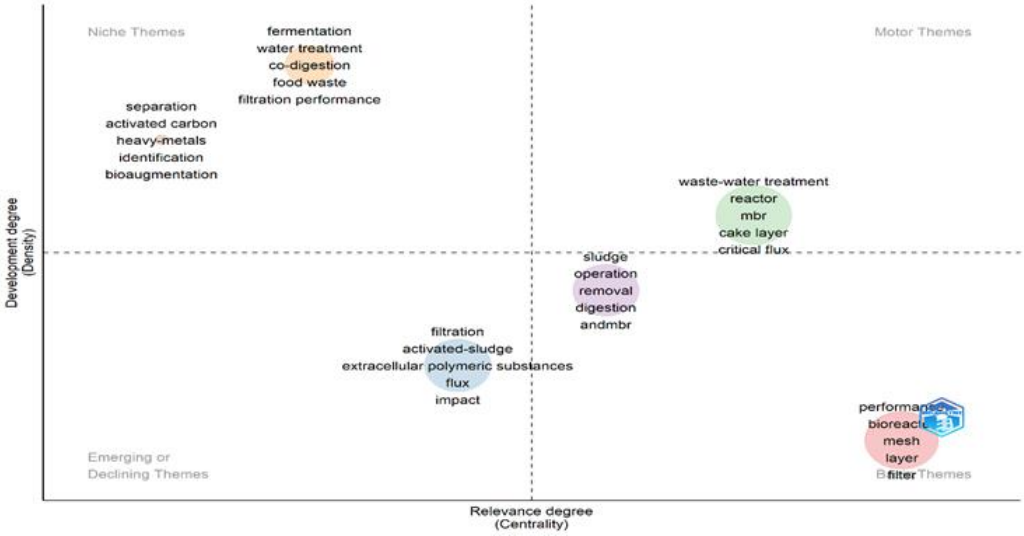


Fig. 7. DMBR thematic map from the top 250 most frequent authors' keywords (clustering algorithm Louvain).

As illustrated in Fig. 7, the well-established and influential themes (motor themes) in DMBR technology include wastewater treatment, reactors, MBR, cake layer, and critical flux. In contrast, keywords such as sludge, operation, removal, digestion, AnDMBR, performance, bioreactor, mesh, layer, and filter are classified as basic themes. While these themes are important to the field, they are currently underdeveloped, exhibiting low density and high centrality. With additional research and analysis, these themes may evolve into motor themes. Emerging and declining themes, such as filtration, activated sludge, extracellular polymeric substances, flux, and impact, are gaining attention and show potential to become significant. These themes often embody novel ideas or methods that question or redefine established paradigms [58].

Niche themes form two distinct clusters: Cluster 1 includes separation, activated carbon, heavy metals, identification, and bioaugmentation, while Cluster 2 consists of fermentation, water treatment, co-digestion, food waste, and filtration performance. Since niche themes represent novel applications in the field and overlap with research hotspots, as indicated by the overlay visualization of keywords discussed in Section 3.5.1, a detailed analysis of these themes in DMBR studies is provided below.

Biohydrogen production through fermentation- generates hydrogen gas via biological processes, primarily utilizing microorganisms such as bacteria and algae. This method provides a sustainable and environmentally friendly alternative to traditional hydrogen production techniques by using renewable resources and organic waste [59]. Some research groups have integrated DMBR technology with continuous biohydrogen production to recover energy during the dark fermentation process [60,61]. These studies employed algal biomass [61] and xylose [60] as substrates and examined the influence of HRT on the hydrogen production rate. Furthermore, additional research explored bioaugmentation in biohydrogen production using DMBR assisted with dark fermentation by adding *clostridium pasteurianum* to improve hydrogen yield from hexose sugars [62]. These findings underscore the growing emphasis on integrating DMBR technology with biohydrogen production as an innovative approach in fermentation processes.

Anaerobic co-digestion involves the simultaneous digestion of two or more organic substrates in an oxygen-free environment to enhance biogas production efficiency. A promising strategy for co-digestion is combining food waste with waste-activated sludge, which takes advantage of their complementary properties, such as an improved carbon-to-nitrogen ratio and enhanced process stability that buffers pH fluctuations [63]. In this vein, Xing et al. [64] explored mesophilic co-digestion of waste-activated sludge and food waste in an AnDMBRto improve biogas conversion efficiency under stable operating conditions. The study found that co-digestion in the AnDMBR yielded higher methane production compared to a conventional continuous stirred tank reactor (CSTR) at the same organic loading rates, highlighting the potential of DMBR technology in anaerobic co-digestion.

These specialized themes (biohydrogen production through fermentation and anaerobic co-digestion) exhibit high potential but remain relatively niche in DMBR research. DM technology can play a central role in elevating these themes into high-impact motor topics. For instance, the self-forming DM layer provides effective solid-liquid separation, allowing continuous recovery of biohydrogen and biogas while maintaining microbial community stability. Optimizing DM properties such as pore size, support material, and layer permeability can enhance process efficiency, reduce fouling, and improve energy yields. In addition, integrating DM-assisted fermentation or co-digestion with standardized operational strategies (e.g., controlled OLR, HRT) enables reproducible and scalable results. Collectively, these advances demonstrate how DMBR applications can transform fermentation and co-digestion from promising niche areas into central research drivers that contribute directly to the advancement and practical implementation of DMBR technology.

The treatment and separation efficiency of DMBR technology has mainly been assessed based on conventional parameters such as COD and SS. Evaluating the efficiency of the DMBR system for recalcitrant pollutants and comparing it with conventional membranes can enhance the competitiveness of DMBR technology [18]. A study by Isik et al. [56] compared DMBR and MBR technologies for removing micropollutants and heavy metals from municipal wastewater. The results indicated that DMs perform comparably to conventional membranes for the pollutants examined, highlighting the potential of DMBR technology in addressing a wide range of contaminants.

Flux enhancers in MBRs are chemical additives designed to improve filtration performance and reduce membrane fouling [13]. Research by Hu et al. [65] demonstrated that incorporating 3 g/L of powdered activated carbon (PAC) into an aerobic DMBR enhanced operational stability by maintaining a higher and stable flux while reducing filtration resistance. PAC also facilitated the quicker formation of the DM layer and expedited recovery following cleaning procedures. A related study assessed the impact of PAC addition on the AnDMBR process, finding that PAC improved COD removal efficiency by 10% and decreased DM filtration resistance by 60%. These enhancements were attributed to PAC's ability to adsorb organics and biopolymers, thus reducing the deposition of small particles on the DM [66].

Overall, recent themes in DMBR technology have predominantly focused on sustainable energy recovery through integrating DMBR with various processes, the technology's effectiveness in removing a broader range of pollutants, and improvements in the filtration performance of DM.

4. Perspective and prospects

The substantial rise in publications over the past decade indicates that DMBR technology is becoming a cost-effective alternative for wastewater treatment. Although research on DMBR shows promising potential and practical applications, this bibliometric study highlights several critical areas that need further investigation to improve its development and implementation.

(i) Application to diverse wastewater types

Keyword analysis indicates that the treatment of municipal wastewater using DMBR technology has received significant attention and is well-documented in the academic community. However, there has been limited effort in applying this technology to treat more challenging types of wastewater, such as landfill leachate and textile wastewater. Therefore, expanding research on DMBR systems to include a broader range of wastewater types—such as industrial, agricultural, and streams contaminated with emerging pollutants—will provide crucial insights into the adaptability and versatility of this technology. Additionally, future studies should assess the economic and environmental impacts of DMBRs when applied to these complex waste streams. This approach will help develop site-specific designs and operational strategies. The focus on emerging contaminants will further demonstrate the flexibility of DMBR systems and their growing relevance in addressing difficult wastewater treatment challenges. Utilizing DMBRs to treat complex effluents can highlight their potential as a resilient and versatile solution across various environmental applications.

(ii) Modelling and Simulation Studies

Advanced modeling tools and simulation frameworks are essential for predicting MBR system performance under varying conditions [67,68]. Current research in DMBR technology lacks these innovations. Therefore, developing advanced modeling frameworks to predict DM formation, membrane fouling dynamics, and pollutant removal efficiencies could significantly optimize operational parameters and enhance our understanding of the mechanisms that influence DMBR performance. Additionally, incorporating machine learning and artificial intelligence into these modeling studies can greatly improve predictive capabilities and support better decision-making. It is also important for these models to include economic analyses, life cycle assessments, and sensitivity analyses to create robust systems that effectively balance operational efficiency, environmental impact, and cost-effectiveness.

(iii) Development of pre-coated DMBRs

Most studies on membrane technology have primarily concentrated on self-forming DM applications, while less attention has been given to pre-coated DMs. The use of pre-coated DMs represents a promising advancement that can enhance filtration performance and reduce membrane fouling [69]. This method may accelerate the formation of DMs and minimize the inherent loss of suspended solids during the early stages of the process [63]. Therefore, future research should explore a variety of coating materials, such as nanoparticles, polymers, or bio-based substances, which can provide specific functionalities, including antibacterial properties or increased hydrophilicity. Studies that focus on these coating materials, application techniques, and their impact on overall system performance could significantly advance the scalability of this technology. Additionally, optimizing the coating process to ensure uniform application and minimize environmental impact could further promote the adoption of this method.

(iv) Hybridization with other technologies

Niche applications of DMBR technology demonstrate the potential for hybridizing DMBRs with other technologies to leverage low-cost filtration. Combining DMBRs with complementary systems presents promising opportunities to maximize resource recovery and enhance treatment efficiency. For instance, integrating anaerobic digestion can boost biogas production, while pairing with advanced oxidation processes can effectively target non-conventional pollutants. Additionally, nutrient recovery systems, such as struvite precipitation, can transform wastewater into valuable fertilizers, supporting the principles of a circular economy. Ongoing research should focus on identifying optimal configurations and operational synergies, as well as evaluating the economic and environmental benefits of these hybrid systems.

(v) Upscaling and real-world implementations

While current laboratory-scale studies provide essential insights into the performance and mechanisms of DMBR systems, their practical viability relies heavily on successful scalability. Transitioning from controlled lab conditions to pilot and full-scale applications involves several technical and operational challenges. These include managing fluctuating operational conditions, optimizing energy efficiency, controlling membrane fouling, and ensuring the long-term mechanical and operational stability of the system. To successfully scale up DMBR systems, it is crucial to implement robust process engineering alongside adaptive operational strategies that can effectively respond to the complexities of real wastewater treatment environments. Conducting comprehensive comparative assessments against conventional treatment technologies—such as activated sludge, traditional MBRs, and other low-energy alternatives—can provide valuable evidence regarding the cost-effectiveness, environmental impact, and long-term sustainability of DMBR applications. These comparisons are essential to demonstrate DMBRs' advantages, including lower membrane costs, reduced chemical usage, and energy savings.

Moreover, interdisciplinary collaborations between academic researchers, technology developers, and industry stakeholders are vital for integrating DMBR systems into existing treatment infrastructures. Such partnerships can foster innovation in system design, advance commercialization pathways, and support policy frameworks that encourage the adoption of sustainable wastewater treatment technologies. Future research should prioritize pilot-scale demonstrations under realistic conditions, along with techno-economic analyses, to bridge the gap between laboratory successes and real-world implementation.

5. Limitations of the study

This bibliometric analysis focused on the trends and advancements in research related to wastewater treatment using DMBR technology. However, the study has some limitations. Although a manual pre-screening was conducted to eliminate irrelevant data, the analysis relied exclusively on publications indexed in the WoS database and did not include articles from non-registered journals. Consequently, significant studies and journals from other databases, such as Scopus, PubMed, and Google Scholar, may have been overlooked. Therefore, future research should consider incorporating additional databases to provide a more comprehensive and validated analysis. Furthermore, the bibliographic data collected were restricted by the specific research keywords used, which were applied only to the titles and abstracts of the publications.

6. Conclusion

This study analyzed 206 articles on DMBR technology, published between 2000 and 2025, sourced from the WoS database. Using bibliometric analysis, social network methods, and keyword visualization, the research examined various aspects such as journal contributions, research categories, author performance, international collaborations, research trends, and emerging hotspots. The findings aim to provide a comprehensive understanding of the current state of DMBR technology research and offer valuable insights to guide future investigations. The journals Bioresource Technology and Chemical Engineering Journal lead in both the number of publications and citations, highlighting their significant role in disseminating influential research findings. The dominant disciplines in advancing and optimizing DMBR technology are chemical engineering, environmental science, and environmental engineering. China significantly leads the field in terms of the number of publications, total citations, and international collaborations. Notable authors making substantial contributions to DMBR technology research include HU Y. (15 publications), KIM S. H. (14 publications), WANG X.C. (13 publications), and WANG Z. (12 publications). Co-occurrence network analysis revealed that current research efforts on DMBR can be categorized into three distinct clusters. The thematic map indicates that hybridizing DMBR with other technologies for resource recovery, as well as improving biological and filtration performance, are emerging niche applications in the field.

This study predicts the continued advancement of DMBR technology in the coming years, as suggested by S-curve fitting analysis. Nevertheless, for this system to gain wider acceptance among practitioners, the technical challenges discussed in this study need to be thoroughly addressed. In particular, advancing the emerging and niche themes identified in this study could accelerate the translation of DMBR technology into broader and more impactful applications. Forthcoming research addressing dynamic layer formation, ensuring long-term operational stability, maintaining system performance under varying operational conditions, and exploring hybrid integration with other treatment systems to leverage the advantages of DM technology can help overcome these challenges and enable the up-scaling and industrial implementation of DMBR technology.

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CRediT authorship contribution statement

A. Ayol: Supervision, methodology, investigation, and writing the paper.
Y. O. Demiral: Investigation, writing paper, methodology.

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Consent to participate

- All authors read and approved the final manuscript.

Data availability

-Data will be made available upon reasonable request.

Declaration of Interest Statement

-The authors declare that there are no conflicts of interest.

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