The Role of Feed Spacers in Membrane Technology: 45 Years of Research

Yazan Ibrahim[1,2], Ersin Aytaç[3,4], Noman Khalid Khanzada[1], Mohamed Khayet[3,5*], Nidal Hilal[1*]

[1] Water Research Center at New York University Abu Dhabi (NYUAD), P.O. Box 129188, Abu Dhabi 129188, United Arab Emirates.

[2] Chemical and Biomolecular Engineering Division, New York University, Brooklyn, New York 11201, United States

[3] Department of Structure of Matter, Thermal Physics and Electronics, Faculty of Physics, University Complutense of Madrid, Avda. Complutense s/n, 28040 Madrid, Spain

[4] Department of Environmental Engineering, Zonguldak Bülent Ecevit University, 67100 Zonguldak, Türkiye

[5] Madrid Institute for Advanced Studies of Water (IMDEA Water Institute), Avda. Punto Com N◦ 2, 28805 Alcalá de Henares, Madrid, Spain

[*] Corresponding authors:

Mohamed Khayet	khayetm@fis.ucm.es
Nidal Hilal	nidal.hilal@nyu.edu

Abstract

Feed spacers are crucial for enhancing the performance and efficiency of membrane-based technologies. Researchers have long focused on optimizing feed spacer designs and materials to improve fluid mixing and mass/heat transfer across membranes. However, these improvements often increase pressure drops, raising energy requirements. Therefore, innovative designs are sought to balance enhanced mass/heat transfer with reduced pressure drops and improved antifouling properties. This study analyzes patterns and trends in the feed spacer field using bibliometric methods, data analysis, and machine learning. The analysis includes 457 articles from the Scopus database, collected on March 5, 2024, covering publications from 1978 to 2023 across 45 journals. The analysis revealed that reverse osmosis technology emerges as the most studied membrane process, with 153 articles. Furthermore, experimental research in this field is preferred over theoretical evaluations, and the impact of feed spacers on mass transfer and pressure drops is the most explored topic, with 197 articles addressing one or more of these phenomena. Additionally, 204 articles focused on feed spacers' role in fouling, scaling, and biofouling, with commercial feed spacers being the most frequently studied. The *Journal of Membrane Science* leads in publication volume with 152 articles, and *Vrouwenvelder J.S.* is the top author in 4 out of 6 metrics. Sentiment analysis of abstracts shows that authors generally express positive sentiments (385 articles) while maintaining an objective (453 articles) and emotion-free (446 articles) writing style.

Keywords**:** Feed spacers, Mass and heat transfer, Membrane fouling, Biblioshiny, Data and text analyses, Machine learning, Emotion analysis, Subjectivity analysis.

1. Introduction

Membrane technology has become a cornerstone in various separation processes, including water treatment, desalination, and wastewater reclamation. Feed spacers are central to the effective operation of such processes as they are crucial in enhancing their performance and efficiency. These spacers are integral components of the spiral-wound membrane (SWM) modules designed to maintain an optimal flow configuration between membrane sheets [1]. They perform several key functions including creating flow channels and enhancing fluid mixing near the membrane surface which eventually can increase mass/heat transfer and reduce concentration polarization (CP) within the feed channel [1–4]. Furthermore, the improved fluid mixing induced by the feed spacer can significantly reduce the interaction between foulants and the membrane surface, thereby minimizing membrane fouling [5,6]. The feed spacers also provide crucial support to the membrane sheets, maintaining their structural integrity under harsh operating conditions, including high pressure and prolonged filtration durations. The overall performance of a membrane technology system, including water flux rate, fouling resistance, and energy consumption, can be profoundly influenced by the design and characteristics of the feed spacers. However, the advantages feed spacers offer to membrane technology systems involve a trade-off between optimizing performance and increasing pressure drop across the feed channel. Higher pressure drops indicate an increase in energy consumption which can negatively affect the overall competitiveness of the system with other conventional methods. A well-designed spacer improves water flux, reduces fouling, and minimizes additional resistance it introduces into the system (i.e., lowers energy consumption) [7].

The conventional designs of feed spacers, typically made from polypropylene (PP) and formed into net-like (i.e., squares) or diamond structures, have been widely used due to their cost-effectiveness and ease of manufacture [7,8]. These spacers are effective in creating flow channels and promoting turbulence but have limitations, such as the creation of dead zones which lead to membrane fouling and increased pressure drop, especially in high-crossflow conditions [9–12]. The latter can lead to greater energy consumption and reduced system efficiency. To address these issues, considerable efforts have been made to innovate both commercially available spacers and those manufactured through advanced technologies like 3D printing [1,13–16]. In recent years, research has focused on improving feed spacers through various modifications and technological advancements. Commercial spacer designs have evolved to include variations in geometry, material composition, and surface treatments [9,16,17]. These innovations aim to enhance the hydraulic performance, reduce fouling, and lower the pressure drop associated with traditional spacers. For example, modifications such as alternating spacer designs and surface coatings have been explored to mitigate fouling and improve mass transfer and cleaning efficiencies [12,18,19]. The advent of 3D printing technology has further revolutionized spacer design by allowing for the creation of complex and tailored spacer geometries that were previously unattainable with traditional manufacturing methods [2,4,20–22]. 3D-printed feed spacers can be designed with intricate structures to optimize flow distribution, minimize dead zones, and improve fouling resistance. These advancements hold the potential to significantly enhance membrane performance and extend the operational lifetime of membrane systems.

The extensive research conducted on feed spacers over the years, along with the evolving trends, directions, and interests of researchers, can be challenging to encapsulate in a single review article. Alternatively, bibliometric and data analyses, which involve the analysis of published literature, can serve as effective tools to achieve this. This type of analysis is crucial for directing resources and efforts towards research areas with high potential for impact which can ultimately advance the field further. For the feed spacers field, the approach allows researchers to investigate the evolution of this field and identify key trends, patterns, and gaps in the existing literature, offering a roadmap for future studies. It also can provide a characteristics evaluation of research published on this topic which can potentially provide valuable information to researchers involved in the development of this research area. Both bibliometric and data analyses were applied widely to many fields including desalination [23], wastewater treatment [24,25], water resource management [26,27], technologies used for water and wastewater treatment [28], adsorptive membranes [29], nanofiltration [30], hollow fiber membranes [31], membrane distillation [32], among others [33]. The widespread application of these techniques indicates their effectiveness in extracting valuable insights and patterns from large volumes of research data, making them invaluable tools for advancing the field under examination. In fact, advances in data storage, computing power, and machine learning (ML) techniques have emphasized the importance of data-driven approaches in science and engineering [34,35]. These methods, such as text mining (TM), bibliometric analysis, natural language processing (NLP), and ML, help process and interpret data, uncover patterns, and manage risks. TM extracts insights from textual data [36], while bibliometric analysis evaluates research trends and collaboration patterns [37–40]. NLP converts natural language into machine-readable forms, addressing grammar, syntax, and other complexities to evaluate and forecast complex information previously buried within large datasets [41–43]. ML techniques, including supervised and unsupervised learning, enable algorithms to predict outcomes and identify patterns across diverse fields [44,45]. Applications span from medical diagnostics to natural language understanding and export forecasting [46–51]. Additionally, NLP often integrates with ML for tasks like topic modeling and zero-shot text classification, enhancing data analysis without prior training [52–54]. These methods can be applied to the field of feed spacers, particularly given the increasing volume of publications on this topic within membrane technology. This growing body of literature heightens the demand for a comprehensive and visually engaging analysis that can effectively map the relevant research landscape.

This study aims to uncover trends and patterns in the evolution of the feed spacers domain by using powerful tools (Python, Orange, Biblioshiny, R, VOSviewer) with advanced analysis methods (ML, TM, bibliometric, exploratory data, and manual analysis). By examining both historical and contemporary research, this study intends to provide a comprehensive overview of spacer innovations, assess their impact on membrane performance, and offer guidance for future research questions. This includes analyzing the distribution of feed spacer applications within membrane technologies and identifying the primary spacer-influenced challenges studied by researchers, such as fouling, biofouling, wetting, and scaling. The study will also examine whether researchers focus on experimental or theoretical evaluations of feed spacers, which may be engineered (i.e.,3D-printed) or commercial. Additionally, the study will uncover which critical parameters, such as mass transfer, pressure drop, and heat transfer, are most frequently focused on in feed spacer research within membrane processes. Besides, the impact of scientific actors such as researchers, journals, universities, etc. on feed spacer literature will be disclosed. The results of these analyses will contribute to the ongoing efforts to enhance membrane systems that utilize feed spacers and push boundaries in this field. Ultimately, the insights gained will help to guide innovations in this field that can improve the efficiency and sustainability of membrane technologies.

2. Data and Methodology

The collection of published research studies for the analysis was obtained by looking into the Scopus database on March 5, 2024. Although there are several scientific databases (i.e., Web of

Science, Dimensions, Google Scholar, PubMed, Cochrane Library, etc.) for this type of study, current studies showed that Scopus may be a preferable alternative due to its vast coverage of relevant journals and trusted indexing database which has high-quality papers from academia [55,56]. The search criteria used in this study are summarized in **Table 1**.

Table 1. Summary of the used search filters in collecting research articles for this study analysis.

Criteria	Description
Article title, Abstract, Keywords	"spacer" AND "membrane"
Source Type	***Limit to:*** Journal
Document Type	***Limit to:*** Article
Publication Stage	***Limit to:*** Final
Year	***Exclude:*** 2024
Language	***Limit to:*** English

After collecting the articles from the database, a journal-based filtration was employed to exclude journals outside the scope of our research (e.g., surgery, robotics, diversity, cell biology, medicine, genetics). A second filtering process (manual screening) was then conducted, resulting in a final dataset of 457 articles. Biblioshiny (version 4.1.4) and VOSviewer (version 1.6.20) were used for bibliometric analysis. The Biblioshiny tool in the R programming language, which features a web-based interface and is part of the Bibliometrix package, offers a comprehensive inspection of scientific mapping [57]. VOSviewer is another tool for bibliometric analysis that focuses on the visualization of bibliographic mapping [58]. Several calculations were carried out to analyze the dataset, with all equations and parameters summarized in **Supplementary Note 1**. This includes global citations (GC), total citations (TC), local citations (LC), collection's compound annual growth rate ($CAGR_C$), the documents' average age measure of the collection (DAA_C) or an item (DAA_{It}), average global citations per document ($AGCD_C$) or an item ($AGCD_{It}$), co-authors per document index (cAD_C), international co-authorships (IcA_C), the average GC per document published in the corresponding year index ($AGCD_{Cy}$), the average normalized GC per document published in the year y ($ANGCD_{Cy}$), document's global citations per year (GCY_i), The average relative global citations of an item ($ARGC_{It}$), Flesch Reading Ease score (FRE), among others.

3. Results and Discussions

3.1. Main statistics and growth patterns in the field of feed spacers

The initial investigation of the dataset, along with a fundamental statistical overview, is a crucial step in the comprehensive data analysis process. These preliminary steps are essential for understanding the structure, type, and general characteristics of the data, as well as for assessing central tendencies (mean, median), distribution, and the overall shape of the data. This foundation is vital for conducting more complex analyses. Consequently, this section begins with an examination of the feed spacer domain using basic statistical measures. Key information about feed spacers in membrane processes is presented in **Table 2**.

Table 2. Overview of general and calculated information extracted from the dataset.

Description	Results
Timespan	1978 to 2023
Number of Journals	45.0
Compound Annual Growth Rate $(CAGR_C)$ *(%)*	8.29
Document Average Age (DAA_C)	9.20
Average Global Citations per Document $(AGCD_C)$	45.2
References	12570
Author's Keywords	966
Authors	1086
Authors of Single-Authored Documents	8.00
Single-Authored Documents	10.0
Co-Authors per Document (cAD_C)	4.32
International Co-Authorships (IcA_C)*(%)*	35.2

As shown in **Table 2**, the dataset covers 457 articles from 1978 to 2023 published in 45.0 different journals. The earliest article on feed spacers, titled "*Mathematical Model of Reverse Osmosis in Parallel-Wall Channels with Turbulence-Promoting Nets*" was authored by Chiolle A. et al. in 1978 [59]. The field of feed spacer in membrane processes seems to be an ever-growing and branching place in the depths of the scientific community. This study area developed at a compound annual growth rate $(CAGR_C)$ of 8.29% (**Table 2**). The documents within the feed spacer domain have an average age (DAA_C) of 9.20 years old. Each article has received an average of

45.2 citations $(AGCD_C)$, contributing to the growth and development of this research area. A total of 12,570 references were cited, and 966 unique keywords were identified, introduced by 1,086 different authors worldwide. On average, each document had 4.32 authors (cAD_C), with an international co-authorship (IcA_C) ratio of 35.2%.

To provide a comprehensive overview of the characteristics of the literature on feed spacers from the extracted dataset, including article length, citation counts, and engagement with existing research, the distribution of key metrics is summarized in **Figure S1**, accompanied by relevant discussions in **Supplementary Information Note 2.** Furthermore, to identify trends within the dataset, the annual publication rates, average global citations per article per year $(AGCD_{C_y})$, average normalized global citations per article per year $(ANGCD_{C_y})$, among other parameters were analyzed and the results are summarized in **Figure 1**.

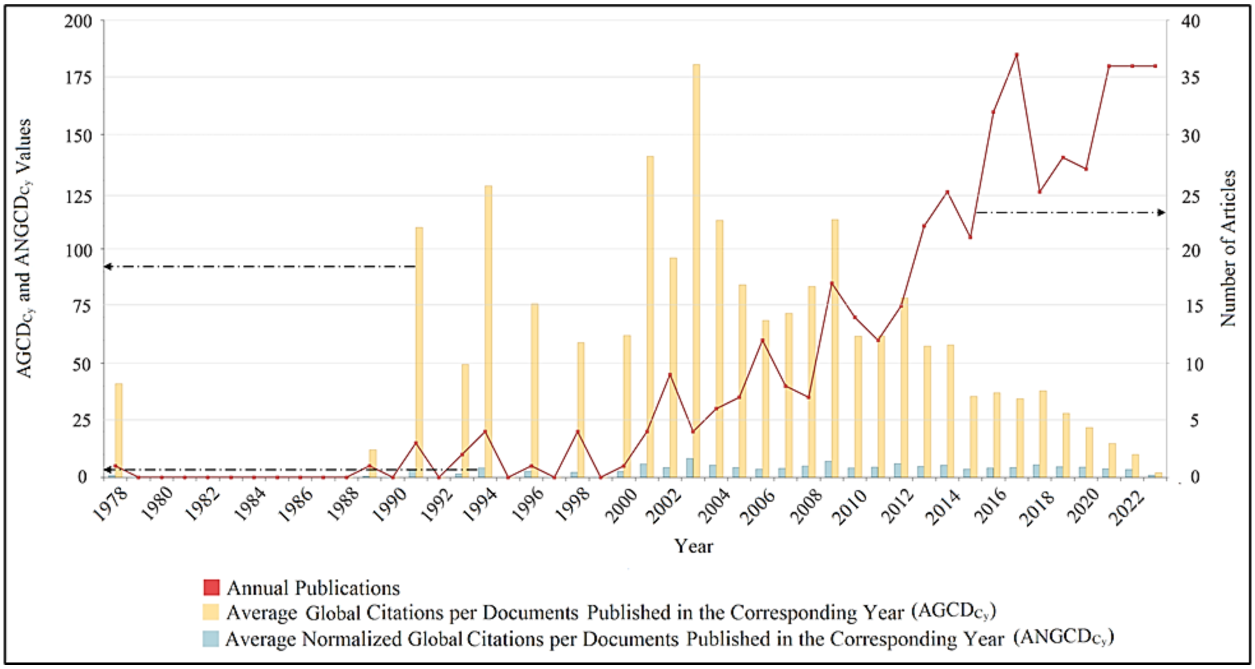

Figure 1. Illustration of the annual number of publications, $(AGCD_{C_y})$, and $(ANGCD_{C_y})$ on feed spacer studies in membrane processes.

As shown in **Figure 1**, research on the utilization of feed spacers in membrane technology began in 1978. However, there was a significant gap in studies on this subject until 1989, with no new publications during that period. It was not until 2000 that the importance of this field was fully recognized, as indicated by a noticeable increase in the number of publications from that year onward. In 2017, the field saw its highest number of publications per year, with 37 articles released as shown in **Figure 1**, marking it as a particularly very active year. Although there was a slight decline in feed spacer studies after this peak, research has remained stable in recent years, with 36 articles published annually over the past three years. Analyzing the $AGCD_{C_y}$ value reveals that the four articles published in 2003 have an average score of 180.8, making them the most influential in the field (**Figure 1**). Even after normalizing the $AGCD_{C_y}$ value to $ANGCD_{C_y}$, the publications from 2003 still hold the highest impact. These four highly influential articles in the field of feed spacers are likely to garner significant attention due to their pioneering contributions to understanding the complex interplay between feed spacer geometry, hydrodynamics, and mass/heat transfer in membrane-based technologies. Each study provided valuable insights into how spacer design and orientation can dramatically influence critical phenomena such as heat and mass transfer, CP, and fouling, which are central to the performance and efficiency of membrane processes. For instance, in both Phattaranawik et al. studies, the role of spacers in enhancing heat and mass transfer in direct contact membrane distillation (DCMD) was investigated thoroughly, offering detailed correlations and alternative methods for evaluating membrane thermal conductivity [60,61]. These findings likely resonated with researchers focused on optimizing membrane distillation (MD) processes, a growing area of interest given the increasing demand for efficient desalination technologies.

Neal et al. investigated the critical flux and particle deposition in spacer-filled channels using the direct observation through the membrane (DOTM) technique and provided crucial experimental data that helped to elucidate how spacer orientation affects fouling behavior [62]. This work likely influenced subsequent research aimed at mitigating fouling, a major operational challenge in membrane systems. Lastly, Geraldes et al. use of computational fluid dynamics (CFD) to model hydrodynamics and CP in SWM modules with ladder-type spacers provided a robust theoretical framework that could be applied to optimize spacer design in reverse osmosis (RO) and nanofiltration (NF) systems [63]. The study's validation through experimental data further reinforced its impact, making it a key reference for both academics and industry professionals looking to enhance membrane module performance.

3.2 Distribution of feed spacer studies according to membrane process type

Feed spacers are crucial for optimizing a wide range of membrane-based processes, underscoring their significant role in enhancing performance across various applications. This study involved a series of categorization processes to uncover detailed insights within the extracted dataset. Initially, the focus was on identifying which types of membrane processes are most frequently investigated in the feed spacer domain and the results are presented in **Figure 2**. It is important to note that 64 studies focused solely on the feed spacer and its impact on hydrodynamics or other factors, without explicitly mentioning the membrane process type (e.g., evaluating the feed spacer within a feed channel or similar setup). For example, García-Picazo et al. conducted a CFD study where they focused on the role of oscillating flow (OF) and feed spacer on hydrodynamics within a 2D zigzag spacer-filled channel [64]. In their analysis, they did not explicitly mention the type of membrane or membrane process used. Instead, they employed a non-permeable dissolving wall boundary condition to model mass transfer within the channel only, which allowed them to bypass simulating transport or mass transfer inside the membrane pores. Therefore, it was not possible to determine the type of membrane or membrane process used in their study. In contrast, the analysis presented in **Figure 2** is based on the remaining 393 articles, each of which explicitly mentioned a membrane process or type in their evaluations. The horizontal bars in **Figure 2** named "**set size**" on the lower left section of the graph represent the total number of times the name of each membrane process is mentioned in the collected dataset. Additionally, the "**Group**" field, represented by vertical bars in green, indicates the number of published articles that explore either intersecting (hybrid or comparative) or non-intersecting (stand-alone) processes. When two or more processes are mentioned in the articles, lines connect the navy-blue squares; however, if a stand-alone process is used, a single navy-blue square is displayed in the "**Group**" field. Lastly, the graphical fragment at the top of the figure shows the distribution of the articles based on their publishing years, organized by columns.

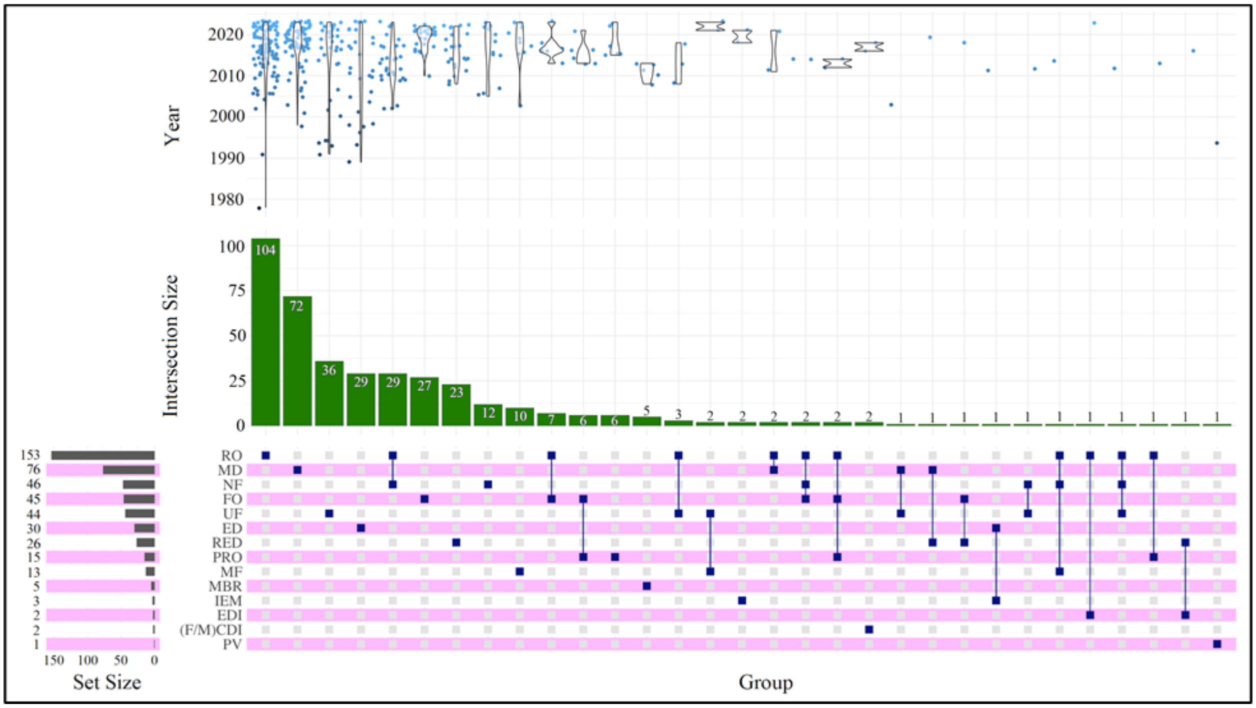

Figure 2. The distribution of studies on feed spacer according to membrane processes (RO: Reverse Osmosis, MD: Membrane Distillation, FO: Forward Osmosis, NF: Nanofiltration, UF: Ultrafiltration, RED: Reverse Electrodialysis, ED: Electrodialysis, PRO: Pressure Retarded Osmosis, MF: Microfiltration, EDI: Electro-deionization/reverse electro-deionization, MBR: Membrane Bioreactor, IEM: Ion-exchange Membrane, (F/M) CDI: Flow-electrode/Membrane Capacitive Deionization, PV: Pervaporation).

It is evident from **Figure 2** that researchers predominantly focus on investigating the role of feed spacers in RO processes. For example, RO was mentioned in 153 articles, with 104 solely focusing on RO applications, 29 exploring hybrid or comparative studies between RO and NF, 7 examining RO and FO, 3 involving RO and UF, and 10 covering other RO combinations. The strong focus on RO with feed spacers is well-founded, as these spacers are essential components of spiral-wound membrane (SWM) modules, which are designed to maintain optimal spacing between membrane sheets, reduce fouling, and enhance water flux [1]. These modules are widely and commercially employed in seawater desalination using RO, as well as in pretreatment (i.e., hybrid system) and water reclamation applications utilizing NF, FO, or UF processes [7,8,65–69]. Similarly, MD ranks second after RO, with 76 articles exploring the role of feed spacers in MD applications. Of these, 72 focus solely on MD, while only 4 examine hybrid systems or comparisons involving MD. The considerable interest in studying feed spacers in MD processes is also driven by their crucial role in commercial modules, where they maintain optimal spacing between membrane sheets and enhance heat transfer, particularly in configurations like air-gap membrane distillation (AGMD) and direct-contact membrane distillation (DCMD) [70,71]. Consequently, researchers have dedicated significant efforts to optimizing feed spacer geometry to enhance mass and heat transfer across the membrane and to minimize energy losses within the feed channel as well as membrane fouling [1].

The NF process, with 46 studies, follows MD in the frequency of investigations involving feed spacers, as shown in **Figure 2**. Among these, 29 studies combined NF with RO, while only 12 focused solely on NF. The FO process was explored in 45 studies, with the majority (e.g., 27 articles) investigating FO as a stand-alone process, and fewer studies combining it with RO (e.g., 7 articles) or PRO (e.g., 6 articles). Similar to RO, the widespread use of SWM modules in commercial NF and FO applications, which incorporate feed spacers in their design, underscores the importance of optimizing feed spacers to enhance flow dynamics and reduce membrane fouling [72–75]. This focus on improving module performance likely accounts for the concentration of research in these areas compared to other membrane applications. The PRO process primarily relies on commercial FO membranes and shares a similar concept with the FO process [76,77]. In PRO, water flows from a low-salinity solution (such as freshwater) through a semi-permeable FO membrane to a high-salinity solution (such as seawater). While this is akin to the FO process, the key difference lies in how the osmotic pressure difference between the two solutions is harnessed for energy generation in PRO. Interestingly, as shown in **Figure 2**, 40% of the studies on PRO that utilized feed spacers also mentioned FO. This overlap is likely due to the fundamental similarities in membrane technology and the critical role that feed spacers play in optimizing the flow dynamics and enhancing the overall efficiency of both processes.

The use of feed spacers with UF and MF membranes is less common in commercial modules. Nonetheless, as shown in **Figure 2**, there is a significant number of studies that examine the impact of feed spacers on membrane technology using UF membranes (44 articles) and noticeably less of MF (13 articles). Most of these studies are often conducted on a lab scale due to the relatively simple and cost-effective nature of UF or MF membranes. Such membranes are easier to handle and model compared to RO and NF membranes because they operate at lower pressures, reducing the complexity of experimental setups. Additionally, these membranes are more readily available and require less energy, making them a practical choice for preliminary investigations. These factors, combined with the ability to quickly observe the effects of feed spacers on filtration performance, make such membranes a convenient option for researchers aiming to understand and optimize the role of feed spacers in membrane processes.

Furthermore, **Figure 2** revealed a notable interest in the study of feed spacers within ED and RED processes, with 30 and 26 articles respectively. This focus underscores the critical role that feed spacers play in optimizing these electrochemical processes. In ED, feed spacers enhance mass transfer by promoting turbulence in the feed channels, which mitigates CP and reduces fouling, thereby improving the efficiency of ion transport across the membranes [78]. Similarly, in RED, feed spacers are essential for optimizing power generation by maintaining optimal flow conditions and minimizing CP, which directly impacts the resistance, ionic flux, and energy output [79,80]. The balance they provide between effective mass transfer and pressure drop is particularly crucial in RED, where energy efficiency is a key factor. These studies highlight the importance of feed spacers in enhancing the operational stability and performance of both ED and RED processes, reflecting their significant contribution to the field of membrane-based technologies.

Feed spacers are also utilized in other membrane processes such as MBR and CDI, though their significance in these applications is often less prominent. From **Figure 2** and besides RO and NF, it is clear that that the number of articles discussing multiple membrane technologies in combination was relatively low. In general, the use of hybrid membrane processes is quite common in the field of membrane technology and is driven by various factors. However, the rationale behind these combinations lies beyond the scope of this article and can be explored in existing literature [81–85]. Lastly, considering intersections with a high number of articles ($\geq$ 10), the average publication years for RO, MD, FO, NF-RO, UF, ED, RED, NF, and MF are 2015.7, 2017.1, 2019.0, 2013.0, 2013.6, 2010.7, 2016.0, 2015.8, and 2017.6, respectively. These results indicate that researchers have increasingly focused on FO feed spacers in recent years, while studies on ED feed spacers appear to be outdated. It is important to note that this trend may also reflect the emergence timelines of the respective technologies.

3.3 The types of research into feed spacers in membrane processes

Research on feed spacers can be categorized as theoretical, experimental, or a combination of both. **Figure 3** illustrates the distribution of these approaches within the collected dataset, highlighting a stronger inclination among researchers toward experimental evaluations. Specifically, 231 articles focused exclusively on experimental investigations of feed spacers in membrane processes, compared to only 123 studies that relied solely on theoretical approaches (**Figure 3**). Experimental research can be conducted in laboratory settings with lab-scale setups or the field with pilot-scale systems. In contrast, theoretical studies, encompassing mathematical, computational, numerical, and analytical methods, are based on system modeling, which involves analyzing, measuring, simulating, visualizing, or describing phenomena using mathematical equations or other methodologies such as computer simulations. This approach enables researchers to gain a deeper understanding of complex systems [86]. A more comprehensive approach involves integrating numerical simulations with experimental investigations and validation when studying feed spacers. Unfortunately, this combined method is the least utilized in the literature, with only 103 studies employing it as shown in **Figure 3**. The reluctance to adopt this approach may stem from the complexity, resource intensity, and expertise required to effectively conduct both numerical simulations and experimental validations simultaneously.

The theoretical approach primarily relied on numerical simulations, specifically computational fluid dynamics (CFD) and direct numerical simulations (DNS). Notably, ≈66.67% of the theoretical studies used these numerical methods, compared to ≈26.83% that employed other approaches and ≈6.50% employing a combination of both (**Figure 3**). CFD is particularly well-suited for analyzing feed spacers, as it allows for detailed modeling of fluid flow within channels that mimic the conditions in commercial SWM modules. These models simulate the actual configuration where feed spacers create spacing between membrane sheets, enabling feed water to flow from the inlet to the outlet side. The simulations involve solving the Navier-Stokes (i.e., momentum equation), continuity, and concentration profile equations, which describe fluid motion and solute distribution, often incorporating approximations to simplify the problem. This approach provides valuable insights into the hydraulic behavior of spacer-filled channels and reveals critical geometric properties of feed spacers that significantly impact performance, guiding further optimization efforts [87]. For instance, Gu et al. used 3D CFD simulations to assess 20 geometric variations of feed spacers, revealing that fully-woven spacers with a 60° feed spacer mesh angle offer the best performance in reducing CP (i.e., fouling) and enhancing water flux (i.e., mass transfer), despite slightly higher pressure drops [88]. Similarly, Shakaib et al. utilized CFD to analyze fluid flow in spacer-filled feed channels of membrane elements, focusing on diamond and parallel spacer geometries [89]. The study found that velocity profiles and average shear stress are significantly influenced by transverse filament spacing, filament thickness, and flow attack angles, while axial filament spacing has a lesser effect. Spacer thickness notably affects pressure drop, and the uniformity of shear stress distribution varies with spacer type and flow conditions.

CFD has reached a new level of maturity, enabling the examination of increasingly complex feed spacer geometries in numerical evaluations. For instance, Chong et al. utilized 3D CFD simulations to assess the performance of twisted feed spacers in membrane channels, demonstrating that these geometries promote vortex generation [90]. This resulted in a 55.0% increase in the Sherwood number (indicating improved mass transfer) and an 8.00% reduction in the friction factor (i.e., pressure drops) compared to conventional ladder-type spacers. Additionally, CFD is instrumental in quickly understanding how even minor modifications to conventional feed spacer designs can impact overall membrane process performance. For example, in another study by Chong et al., simple alterations to the node geometries and sizes of ladder-type spacers significantly influenced RO performance [91]. Their findings showed that column nodes outperformed spherical nodes, increasing the Sherwood number by 25.0%, though at the cost of a 44.0% higher friction factor, and column nodes also delivered higher flux at elevated feed inlet velocities due to enhanced mixing effects.

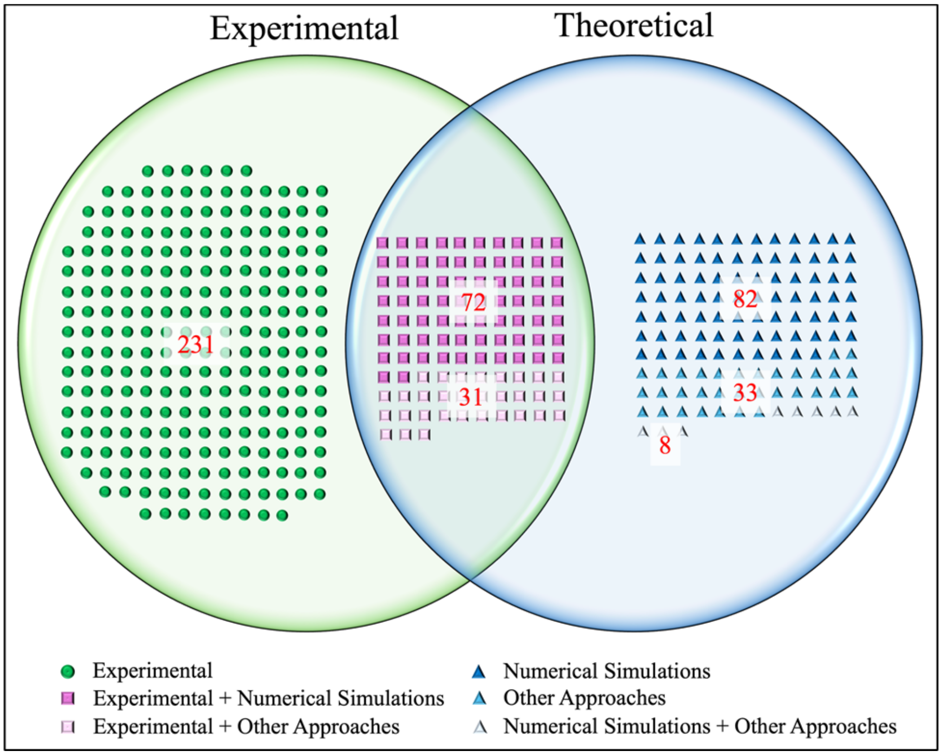

Figure 3. Distribution of experimental, theoretical, and combined studies on feed spacers in membrane processes.

Other theoretical approaches for evaluating feed spacers in membrane processes include trial-and-error methods and the use of approximations to solve the governing equations (e.g., Nernst-Planck, solution velocity, and limiting current density equations). For example, Tanaka used this approach to evaluate the impact of a spacer on the limiting current density in an ion-exchange membrane electrodialyzer [92]. The results showed that while spacers in an ion-exchange membrane electrodialyzer are typically intended to promote turbulence, they can obstruct laminar flow, create dead spaces, and reduce the limiting current density. To counteract this, increasing solution velocity and Reynolds number is necessary to induce turbulent flow, thereby enhancing the limiting current density. Other researchers combine numerical simulations with additional theoretical approaches to gain a more comprehensive understanding of the role of feed spacers in membrane processes. Although this method is rare, accounting for only ≈6.50% of theoretical studies (as shown in **Figure 3**), integrating numerical simulations with other approaches can provide a more nuanced and accurate assessment of spacer performance and optimization. For example, Binger and Achilli combined CFD simulations with ML to analyze how different spacer geometries impact pressure loss and CP in membrane channels [93]. They performed 321 CFD simulations to gather high-fidelity data, which was then used to train ML models for more accurate predictions of pressure loss and mass transfer coefficients in spacer-filled membrane channels. By integrating these surrogate models with a particle swarm optimization algorithm, they identified optimal spacer designs that effectively balance CP with pressure losses across various feed flow velocities in the channel. This approach can be expanded to investigate additional phenomena in membrane channels with feed spacers, such as scaling, fouling, and heat transfer, offering a comprehensive and more accurate tool for optimizing membrane system performance.

Among the 457 studies in the collected dataset, 103 combined numerical simulations with experimental investigations to evaluate feed spacers in membrane processes, as shown in **Figure 3**. This dual approach is valuable for validating numerical results and developing new empirical equations. For instance, Schilling and Glade combined experimental investigations with CFD simulations to study heat transfer in spacer-filled channels within an MD system [94]. Their work revealed significant influences of spacers on heat transfer, leading to the derivation of a new empirical Nusselt correlation that accurately represents their experimental data with a deviation of just 10%. This combined approach provided deeper insights and allowed them to refine predictive models for heat transfer in the MD system with feed spacers. On the other hand, Yu et al. introduced a novel feed spacer design for SWM modules, comparing two variations, Arch-Hole and Arch, against a conventional net-type feed spacer [95]. CFD simulations indicated that the Arch-Hole design achieved a more uniform velocity distribution with fewer dead zones indicating better antifouling performance and higher water flux. These findings were validated through experimental tests using optical coherence tomography and water flux measurements, which confirmed that the Arch-Hole spacer led to less foulant accumulation and maintained higher flux values. By using experimental results to validate the CFD simulations, this study effectively demonstrated how optimized spacer designs can significantly improve membrane performance. Other researchers have combined experimental results with new data-driven fouling models to predict RO membrane performance in practical settings. For example, Gaublomme et al. developed a hybrid model integrating a common solution-diffusion model with a data-driven fouling prediction model [96]. This approach used a recurrent neural network with long short-term memory (RNN-LSTM) to enhance predictions of RO membrane resistance with feed spacers over time, significantly improving performance compared to traditional models. The hybrid model, calibrated with a long-term dataset from a full-scale RO system running for 8 months, showed strong potential for real-time applications, such as advanced control and predictive scenario analysis. Overall, research on feed spacers involves a mix of experimental and theoretical approaches. While experimental studies provide practical insights, theoretical research, especially through numerical simulations like CFD, offers detailed modeling of spacer performance. Several review articles have comprehensively summarized the literature on modeling methods for various membrane processes in the presence of feed spacers, providing valuable resources for researchers [97–100]. Combining numerical simulations with experimental data is less common but highly effective. This hybrid approach validates simulations and improves empirical models, leading to better spacer designs and enhanced membrane performance.

3.4 Frequently examined parameters and challenges in feed spacers research

The primary parameters examined in most spacer-related studies include mass transfer, heat transfer, and pressure drop. Researchers focus on how feed spacer geometry influences these parameters and the distribution of these studies is illustrated in **Figure 4 (A)**. In the context of **Figure 4 (A)**, mass transfer refers to the movement of mass across the spacer-filled feed channel or membrane. Most studies in the literature adopt the impermeable-dissolving walls model to evaluate mass transfer in the presence of a feed spacer, with only a few considering permeable membranes. Experimentally, mass transfer can be measured using osmotic pressure and film models to determine the Sherwood number and mass transfer coefficient [20,101]. Theoretically, it is determined by coupling the Navier–Stokes equations, which describe fluid flow, with the convection-diffusion equation, which governs mass transport [102]. The results are typically analyzed using the dimensionless Sherwood number or mass transfer coefficient. Overall, an improved mass transfer indicates better feed spacer performance in generating turbulence and shear stresses on the membrane surface, ultimately leading to enhanced membrane process performance.

Heat transfer enhancement is particularly relevant in MD processes, where a higher heat transfer coefficient across the thermal boundary layer leads to improved MD performance [103]. Experimentally, this can be determined by measuring temperatures on the feed and permeate sides of the membrane, as well as water vapor pressure and flux [103]. Theoretically, it involves solving the continuity, momentum, and energy equations, followed by determining the Nusselt number to quantify heat transfer improvement due to fluid motion [104,105].

The pressure drop across the channel is a critical parameter for assessing the energy requirements of the membrane process in the presence of feed spacers, as their presence often leads to higher pressure drops which necessitate increased pumping energy to maintain membrane performance. This can be measured experimentally using pressure gauges at the inlet and outlet of the feed channel or theoretically by calculating the global, drag, or Fanning friction factors, as well as the power number [5,6,106].

In the collected dataset, as shown in **Figure 4 (A)**, only 44 articles focused exclusively on either pressure drop or mass transfer in their evaluations. These studies chose to isolate one parameter, examining its impact on membrane processes with feed spacers. The majority of studies, represented by 109 articles, analyzed both pressure drop and mass transfer together. This focus on dual parameters is likely since most membrane-based technologies, such as RO, NF, UF, MF, and MBR, are pressure-driven processes. These processes make up a significant portion of the dataset, as shown earlier in **Figure 2**. In such systems, both mass transfer and pressure drop are critical factors that feed spacers can directly influence. Therefore, extensive research has been conducted to optimize feed spacer designs that enhance fluid mixing and turbulence near the membrane surface leading to improved mass transfer. Improved mass transfer leads to better overall membrane performance while reducing feed channel pressure is crucial for minimizing energy requirements. Higher pressure drops are directly correlated with increased energy consumption, which has significant environmental implications for membrane processes.

In the literature, numerous studies have explored the interplay between mass transfer and pressure drop to find the optimal feed spacer design. For instance, Li et al. investigated feed spacers with modified filaments, twisted tapes, and multi-layer structures, assessing their impact on mass transfer (via the Sherwood number) and pressure drop (via the power number) [107]. Sreedhar et al. used 3D-printed feed spacers based on triply periodic minimal surface (TPMS) mathematical architectures in RO and UF experiments to identify the designs that provided the highest mass transfer enhancement with the lowest increase in pressure drop [2]. Similarly, Chong et al. employed small-scale CFD analysis to evaluate pressure drop and mass transfer performance in RO modules with submerged feed spacer designs featuring column nodes and spherical nodes [91]. However, some studies focused solely on one parameter as shown in **Figure 4 (A)**. For example, Park et al. examined mass transfer in NF membrane applications [4], while Xie et al. studied mass transfer in osmotically driven processes such as FO and PRO [108]. Studies that concentrated only on pressure drop include Sousa et al.'s evaluation of hydrodynamics in desalination membranes with feed spacers [109], Wang et al.'s analysis of feed spacers in single- and two-phase flows [110], and Gurreri et al.'s assessment of woven feed spacers for pressure drop in reverse electrodialysis (RED) channels [111].

Heat transfer, though less frequently studied compared to mass transfer and pressure drop, plays a crucial role, particularly in specific applications like MD. As shown in **Figure 4 (A)**, only 17 studies considered the combined effects of heat transfer, mass transfer, and pressure drop, while 28 focused on mass transfer and heat transfer together. However, only 9 studies examined heat transfer alongside pressure drop, and a mere 6 studies focused exclusively on heat transfer in their evaluation of feed spacers in membrane processes.

The relatively low emphasis on pressure drop in heat transfer studies may be attributed to the unique nature of MD, where thermal gradients drive the process rather than hydraulic pressure. Unlike processes such as RO or NF, where pressure drop directly impacts energy consumption and system performance, MD relies on the efficient transfer of heat to vaporize water. In this context, optimizing the heat transfer across the membrane surface is more critical, while pressure drop becomes less of a concern. For example, researchers investigating MD often prioritize the heat transfer coefficient across the thermal boundary layers, as improved heat transfer directly correlates with better process efficiency [103]. This focus on thermal management explains why pressure drop might not receive as much attention in these studies, as it does not significantly impact the energy dynamics of the MD process. Mass transfer in MD is also a critical aspect of the process, just as it is in pressure-based membrane processes such as RO, NF, and UF, among others. However, the mechanisms and governing equations for mass transfer in MD are significantly different due to the distinct nature of the processes. In MD, mass transfer occurs via vapor transport through a hydrophobic, microporous membrane, and is typically described using the Knudsen diffusion, Poiseuille flow, molecular diffusion models, or a combination of these models [112]. The driving force for mass transfer is the vapor pressure difference across the membrane, which is induced by a temperature gradient between the hot feed side and the cold permeate side. In 28 articles where heat transfer and mass transfer were discussed together, researchers tried to understand the impact of feed spacers, membrane structure, and operational variables on different membrane distillation configurations like direct contact (DCMD), air gap (AGMD), and sweeping gas (SGMD) [60,113–116]. On the other hand, studies on heat transfer and pressure drop together included experimental studies on conventional and novel feed spacers [117], experimental investigation of fluid and heat transport within the spacer-filled channels with various spacer flow attack and filament angles[118], and the performance comparison between overlapped and woven spacers [119], among others. The studies dealing with all 3 parameters (mass transfer, heat transfer, and pressure drop) consist mostly of CFD simulations [120–124], then investigations like evaluation of spacer-induced hydrodynamic mixing using particle image velocimetry [125], spacer structure on the enhancement of heat and mass transfer [126], entrance length effects on Graetz number scaling in laminar duct flows with periodic obstructions [127], among others.

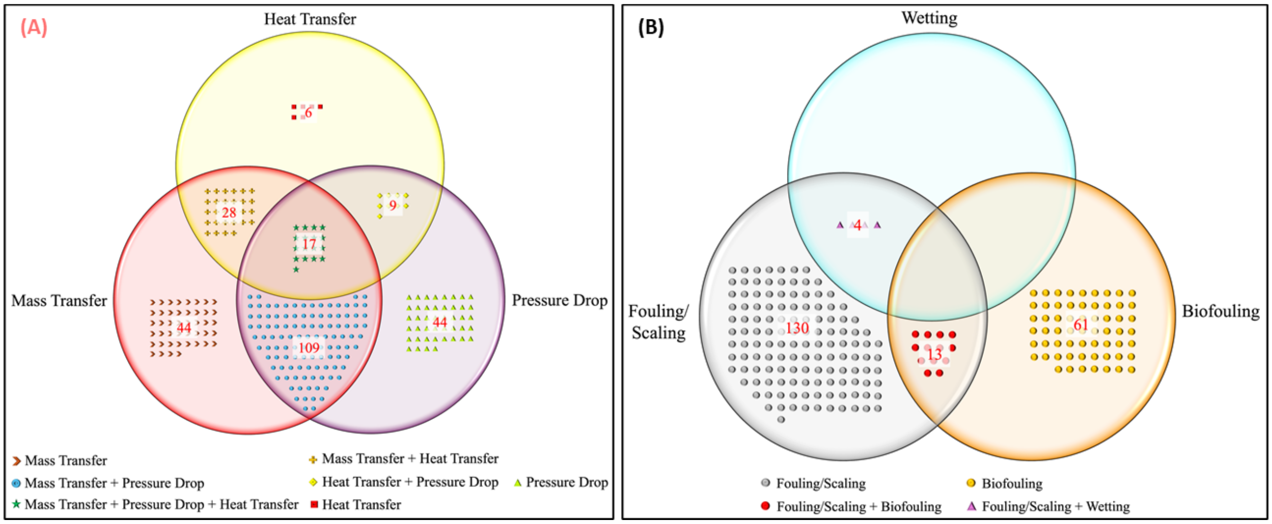

Figure 4. (A) Overlap of studies addressing mass transfer, heat transfer, and pressure drop, and **(B)** Overlap of studies addressing the primary challenges in membrane processes with feed spacers.

In membrane processes, one of the key areas of research focuses on addressing significant operational challenges, primarily membrane fouling, scaling, and biofouling. These issues can severely impact the efficiency and longevity of membrane systems. Over the years, researchers have dedicated extensive efforts to developing anti-fouling membranes to mitigate such problems [128–133]. Simultaneously, investigations have been conducted to understand the role of feed spacers in addressing these challenges [15,16]. Surprisingly, some studies have revealed a correlation between feed spacers and exacerbated membrane fouling [134]. Membrane fouling refers to the accumulation of unwanted materials (e.g., organic or inorganic material) on the membrane surface or within its pores, leading to a decline in membrane performance [135]. Scaling is a specific type of fouling where inorganic salts precipitate and form a layer on the membrane, obstructing the flow and reducing permeability. Biofouling involves the growth of microorganisms on the membrane surface, forming a biofilm that can significantly hinder the filtration process. Feed spacers can help mitigate these issues by promoting turbulence within the feed channel and enhancing fluid mixing. This affects the interaction between foulants and the membrane surface which subsequently reduces foulant deposition and disrupts the formation of biofilms and scale layers on the membrane surface.

As illustrated in **Figure 4 (B)**, 130 studies have investigated the impact of feed spacers on membrane fouling or scaling, while only 61 studies have focused on their effect on biofouling.

These studies encompass various membrane processes, including RO [96], UF [136], NF [4], MD [137], and RED [79], among others. The types of feed spacers used in these investigations span a diverse range of water sources, such as natural seawater and sewage effluents [138], oil/water emulsion [139], municipal wastewater [140], and synthetic seawater [141]. Researchers generally focus on redesigning feed spacer geometry to combat various types of membrane fouling and biofouling. These efforts include but are not limited to, the development of sinusoidally curved spacers [142], honeycomb-shaped spacers [4], vibrating wave-like spacers [143], column-type spacers [22], helical filament spacers [144], 3D-printed TPMS-based gyroid spacer [2,145], modified filament size and angles [146], among others.

Modified or redesigned feed spacers typically enhance turbulence and fluid mixing near the membrane surface, which in turn influences the intensity of shear stress on the membrane. Increased fluid turbulence generally leads to higher shear stress, which has a dual effect: it enhances mass transfer and reduces membrane fouling. For instance, Yanar et al. demonstrated that a novel honeycomb-shaped feed spacer geometry generated well-distributed and higher shear stresses near the membrane surface during FO experiments [147]. This effectively weakened the adhesion of foulants to the membrane, thereby reducing overall membrane fouling. In contrast, Kerdi et al. observed that regions with higher shear stress concentration, particularly beneath the spacer filaments of a helical-type feed spacer, can lead to rapid bacterial attachment [144]. This, in turn, resulted in increased biofilm growth and it’s spread across the membrane. These differing observations suggest that more research is needed to fully understand the role of feed spacers in membrane processes. The varying effects seen in different studies indicate that the design and geometry of feed spacers are crucial factors that can either mitigate or exacerbate membrane fouling. Thus, further investigation is essential to reveal the actual role of feed spacers and to optimize their design for enhancing membrane performance across different applications.

Coating feed spacers or fabricating them from anti-fouling and anti-biofouling materials is another effective strategy to combat fouling, scaling, and biofouling. For instance, Thomas et al. enhanced scaling mitigation in DCMD by coating a novel hybrid feed spacer based on TPMS with various nanomaterials, including fluorinated silica, graphene oxide (GO), and reduced graphene oxide (rGO) [148]. Similarly, Sreedhar et al. applied β-FeOOH nanorods to feed spacers to improve foulant degradation and facilitate membrane cleaning [149]. Jeong et al. utilized 3D printing to create diamond-shaped feed spacers from carbon nanotube (CNT) material to reduce membrane scaling during MD experiments [150]. Additionally, Rice et al. employed biocidal silver coatings on commercial polypropylene feed spacers to minimize biofouling in bench-scale reverse osmosis (RO) systems [151]. Overall, these coatings can reduce the interaction of foulants with feed spacers and, in some cases, even degrade the foulants. The anti-fouling and anti-biofouling properties of the coatings create a surface that is less prone to foulant adhesion, which minimizes the accumulation of unwanted materials on the spacers.

In analyzing the collected dataset, only 4 articles addressed the issue of wetting in addition to fouling and scaling in membrane processes, as illustrated in **Figure 4 (B)**. Wetting is predominantly a challenge in MD and membrane contactor processes. Alpatova et al. presented an innovative solution by using electrically conductive Pt-coated feed spacers in MD to achieve instantaneous wetting detection [152]. By utilizing these novel spacers and measuring the electrical current generated during pore wetting, this method provides faster and more accurate wetting detection compared to traditional conductivity measurements, enabling early identification of membrane impairment.

3.5 Insights into feed spacers types and fabrication techniques

In the analysis of the collected dataset on feed spacers, we identified the need to classify these spacers by their type and fabrication technique. The feed spacers used in the studies (excluding articles where the spacer type was unclear) were divided into two main categories: commercial and engineered as shown in **Figure 5**. The commercial category includes modified and raw (i.e., unmodified or commercial-like) feed spacers geometries, while the engineered category includes feed spacers produced via 3D printing techniques and those fabricated using other conventional methods. This segmentation allows for a better understanding of the trends in feed spacer development and usage over time, as illustrated in **Figure 5**. As shown in the figure, 178 studies utilized raw commercial feed spacers in their evaluations. However, among these, 18 focused on 3D-printed spacers, 5 on fabricating spacers using conventional techniques, and 9 on modified commercial feed spacers. In these cases, the commercial spacer was primarily used as a reference to compare the performance of newly developed spacers. Consequently, the actual number of studies that exclusively used commercial feed spacers is 146.

The prevalence of studies using commercial feed spacers can be attributed to the fact that commercial feed spacers are readily available, making them convenient for researchers to obtain and use. This accessibility allows for easier replication of experiments and comparison of results across different studies. It is important to highlight that commercial feed spacers are available in a wide range of shapes (e.g., diamond and square), designs (including varying mesh sizes and filament angles), and thicknesses. Some studies focus on evaluating a single type of these commercial spacers, while others compare different types sourced from various manufacturers to assess their performance in membrane processes. Examples of such studies include analyzing the hydrodynamics induced by different commercial feed spacer designs and their correlation with mass and heat transfer [125,153], examining the impact of commercial spacers on hydraulic performance and antifouling in membrane process [10,12], investigating particle deposition behavior on membrane surfaces with commercial spacers [154], and evaluating the design of full-scale modules [155], etc. On the other hand, modifying commercial feed spacers was less common with only 31 studies and involved coating the spacers with specific antifouling or antibiofouling materials such as CuO [156], polysulfobetaine methacrylate (pSBMA) zwitterionic polymer [157], organo-selenium [158], nanosilver [159], neutral (polyHEMA-co-PEG$_{10}$MA), cationic (polyDMAEMA) and anionic (polySPMA) hydrogels [160], crystalline ZnO nanorods [161], silver, copper and gold coatings [9], etc.

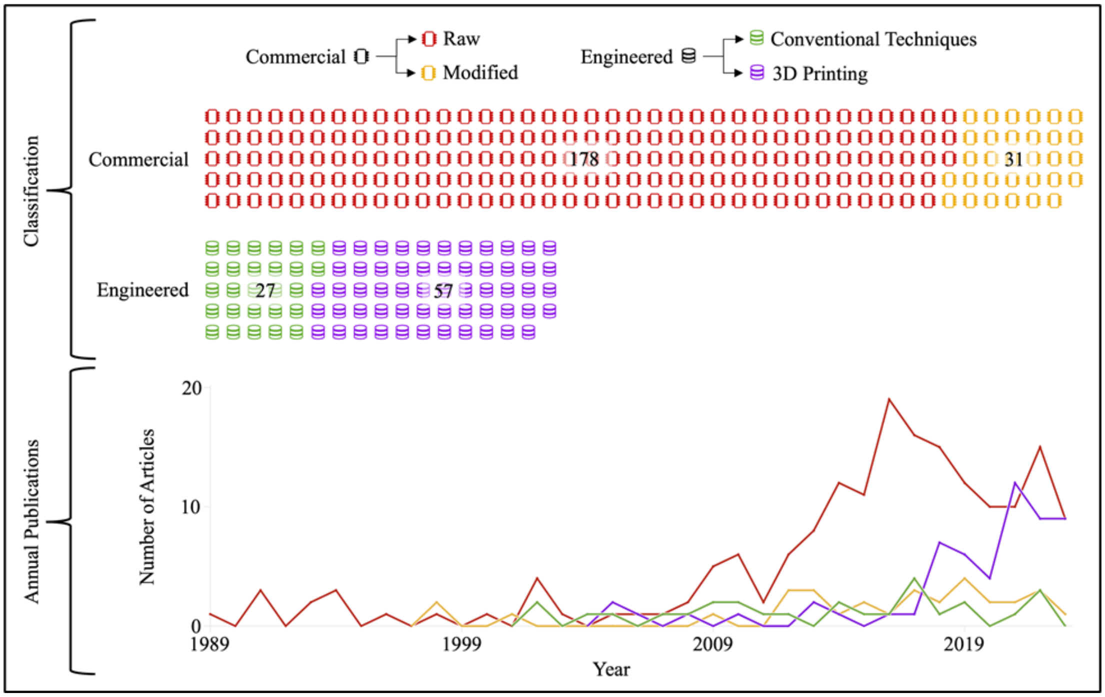

Figure 5. Classification of feed spacers by spacer type and fabrication technique used in the feed spacer-related studies.

Engineered feed spacers are designed to stand out from the commercial spacers, while usually using the latter as a benchmark for performance comparison. Among those, 27 utilized conventional techniques to create these engineered spacers. For example, Ponzio et al. assembled a woven feed spacer using commercial black rubber wires [162], while Xie et al. fabricated various sinusoidal-shaped spacers by milling these geometries into brass or plastic blocks [163]. Vermaas et al. used non-ion-conductive wires to construct both a standard woven spacer and an innovative helical structure by assembling a weft and twisted filament spacers [164]. Cancilla et al. created spacers using PVC rods, rubber wire, or plastic spheres/sticks to form overlapped, woven, and spherical spacers, respectively [117]. Additionally, Koutsou et al. glued polyethylene filaments with a 1.00 mm diameter to form various feed spacer shapes [165].

Engineered spacers that are 3D-printed seem to witness growing attention with 57 studies dedicated to this area as shown in **Figure 5**. 3D printing has revolutionized the manufacturing process with advantages such as the ability to create different complex geometry designs, in-situ production processes, promote customized production, and produce less waste with the potential of recycling material [166]. In fact, the feed spacers field, in particular, experienced significant alterations and advancements since the emergence of 3D printing [1]. This technology allows for the creation of highly customized spacer geometries tailored to optimize fluid dynamics and mitigate fouling, enabling researchers to explore innovative designs that are difficult or impossible to achieve with conventional manufacturing methods. For example, Sreedhar et al. utilized complex TPMS designs such as Schwarz crossed layers of parallel (CLP), Schwarz primitive (Schwarz-P), and Schoen Gyroid to 3D-print innovative feed spacers using selective laser sintering (SLS) 3D printing technique [2]. Such feed spacer designs showed superior performance in terms of water flux and lower pressure drops when compared to commercial diamond-shaped spacers. Other examples of innovative and complex 3D-printed feed spacers include helical spacer designs [144,167], honeycomb-shaped feed spacers [147], gyroid and herringbone feed spacers [168], column and perforated column-type spacers [22,169], honeycomb-like $Ti_3C_2T_x$ MXene-based feed spacers [170], among others.

Figure 5 also illustrates the number of annual publications related to different types of feed spacers. Up until 1998, research was exclusively focused on commercially available spacers. In 1998, two studies began exploring the modification of these commercial spacers by surface coating and chemical modification techniques [171,172]. The first self-fabricated spacer (e.g., ladder-type spacer), produced using conventional techniques, was introduced in membrane processes in 2002 by Geraldes et al. [72,173]. The concept of manufacturing spacers via 3D printing emerged shortly thereafter in 2005, quickly capturing the attention of researchers [107]. Although commercial spacers remained the most widely used and studied each year, 3D-printed spacers gained significant momentum, surpassing all other types of spacers with 12 publications in 2021. This trend underscores the growing preference for 3D printing in the fabrication of feed spacers, reflecting its advantages over traditional methods.

3.6. Top journal sources for feed spacers articles, leading authors, and their collaborations

A key aspect of bibliometric analysis is identifying the most influential journals within a specific field of study. Journals play a crucial role as primary sources for advancing scientific knowledge, collecting research findings, and disseminating information. Moreover, this type of analysis serves as a valuable resource for researchers focused on feed spacer development and their influential role in membrane processes, guiding them on the most suitable journals for publishing their work. The top 10 journals in the dataset, ranked by the number of published articles and their associated metrics as well as their publication trends over time are presented in **Figure 6 (A)** and **(B)**. The figure revealed that the *Journal of Membrane Science* is the leading publication across all key indicators in the field of feed spacers (**Figure 6 (A)**). With 152 articles on this topic, it has accumulated 10,482 global citations (GC), and dominates the h, g, and m-indices with scores of 63, 97, and 1.853, respectively, maintaining its leading position. *Desalination Journal* emerges as another significant journal in this domain, with 99 published articles on feed spacers. The high performance of the *Water Research* journal in various metrics, including GC and indices scores, suggests that it has recently gained prominence among scientists focusing on feed spacer research. Furthermore, **Figure 6 (B)** shows that the *Desalination* Journal was the first to publish on this topic in 1978 and has periodically covered this topic through 2023. Meanwhile, the *Journal of Membrane Science* boasts the longest continuous coverage of the field, spanning 24 years from 2000 to 2023, and set a record in 2018 with 12 articles published on the subject.

Figure 6. (A) Top 10 journals, and **(B)** Production overtime of the top 10 journals in feed spacer development and evaluation in membrane processes.

Parallel to identifying the most influential journals, analyzing the leading contributors to feed the spacer research field offers insights into prominent research groups and facilitates the tracking of scientific collaboration networks. **Figure 7** presents the top 10 authors based on publication volume and their associated metrics as well as their production overtime in the field of feed spacer development and evaluation. Notably, the 10th position includes both the 10th and 11th authors due to a tie in the number of publications. As shown in **Figure 7 (A)**, the author *Vrouwenvelder J. S.* stands out as the leading author in the feed spacer field, excelling in four of the six metrics shown: number of articles (37), fractionalized article value (AF_{au}) (7.27), h-index (27), and g-index (37). *Fane A. G.*, another prominent contributor with 25 articles, holds the highest GC count in the field with 3,112 citations. On the other hand, *Ghaffour N.* leads in the normalized h-index, and the m-index with a value of 1.857, reflecting a significant impact relative to the time spent in the feed spacer field.

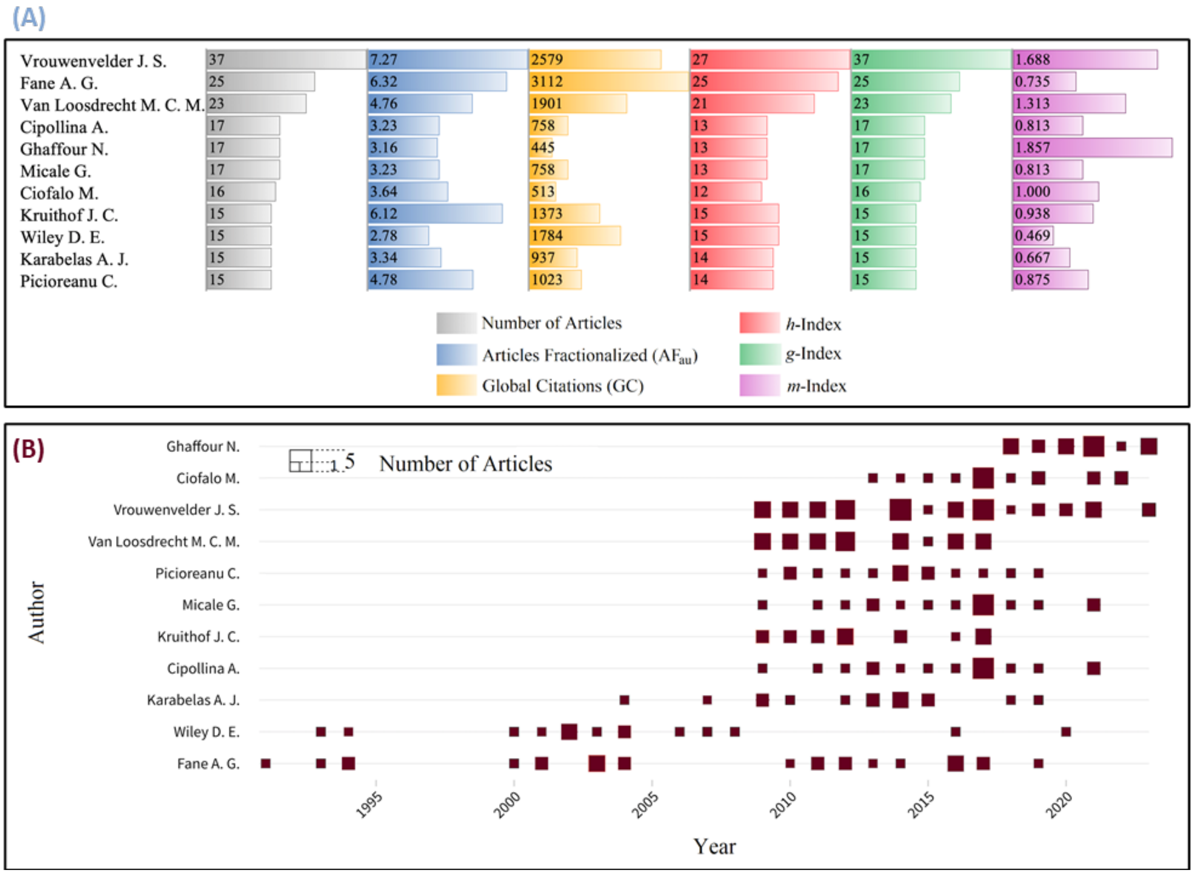

Figure 7. (A) Depiction of the top 10 leading authors with their corresponding metrics, and **(B)** Their production overtime in the field of feed spacer development and evaluation in membrane processes.

The temporal publication performance of these top 10 leading authors was also analyzed to provide insights into their productivity and consistency over time. This trend is detailed in **Figure 7 (B)**, which illustrates the publication output of these leading authors. When examining this figure, it becomes clear that *Fane A. G.* has the longest track record of scientific studies on feed spacers, spanning from 1991 to 2019. However, *Vrouwenvelder J. S.* holds the record for the longest continuous period of research in this domain, maintaining an active presence for 12 years, from 2009 to 2021. Moreover, the analysis highlights that the highest number of articles published in a single year by an author in this field is five, a feat achieved by *Ciofalo M.*, *Cipollina A.*, *Ghaffour N.*, *Micale G.*, and *Vrouwenvelder J. S.*, with *Vrouwenvelder J. S.* accomplishing this twice. This indicates not only their significant contributions but also the sustained momentum in their research efforts. Such patterns reflect the evolving focus and dedication of key researchers in advancing the understanding and development of feed spacers in membrane processes.

The collaboration between these researchers was also investigated through the establishment of a co-authorship network shown in **Figure 8**. In the scientific community, "network" usually refers to connections and collaborations between scientists. Networks enable scientists to stay updated on developments, share findings, collaborate on projects, and access career opportunities. The co-authorship network shown in **Figure 8** was constructed from the dataset on feed spacers, with a minimum threshold of 9 documents per author applied to enhance the readability and interpretability of the figure. In **Figure 8**, the size of each rectangle (node) is proportional to the number of articles authored by an individual, while colors indicate different social clusters within the network. The thickness of the links (edges) reflects the volume of co-authored publications. The figure revealed five primary networks in the feed spacers field, with each network containing between two and five authors. Inter-cluster connections are sparse, primarily occurring between the blue and red clusters, whereas intra-cluster connections are more prevalent.

Cluster-based metrics showed that the red cluster, including the authors *Ghaffour N.* and *Qamar A.*, has the most recent publications with an average year of 2020.46. Conversely, the oldest publications seem to appear in the green cluster, which dates back to 2011.55 (average publication years) and leads in both average citations per document (109.41) and average relative citations (1.41). Individual analysis revealed the strongest connection between *Van Loosdrecth M. C. M.* and *Vrouwenvelder J. S.*, with 21 co-authored articles. The author *Vrouwenvelder J. S.* holds the highest number of connections (i.e., 6 connections) and has collaborated on 71 documents. *Liang Y. Y.* published the most recent articles, with an average publication year of 2020.64. *Fane A. G.* leads in average citations per document with a score of 124.48, while *Tang C. Y.* tops the list for average relative citations with a value of 1.61.

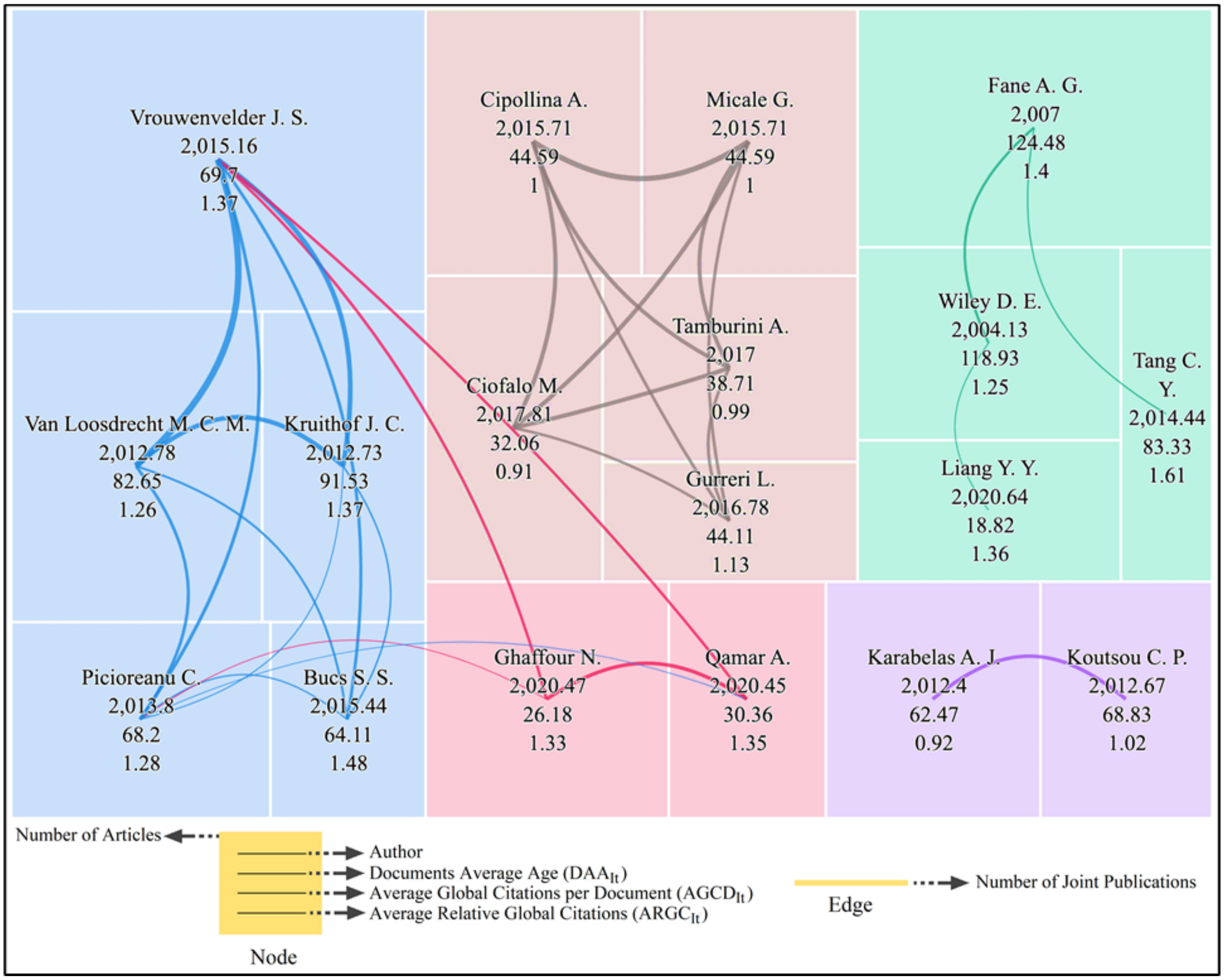

Figure 8. Depiction of the co-authorship analysis for authors working on feed spacers development and evaluations (weights = documents, minimum number of documents of an author = 9, and clusters with single item were removed).

3.7 Influential articles, authors affiliations and leading countries in feed spacers research

This section explores the key contributions that have shaped the field of feed spacer research by identifying the most influential articles, leading author affiliations, and the top contributing countries. For instance, the dataset was also analyzed to identify the most influential articles in the field of feed spacers to provide researchers with the most impactful findings and theories. The results are illustrated in **Figure 9 (A)** which presents the top 10 influential articles based on global citation metrics, offering a clear view of the seminal works that have shaped current knowledge and ongoing research in feed spacer domain. The article titled *"Heat Transport and Membrane Distillation Coefficients in Direct Contact Membrane Distillation"* by Phattaranawik et al., published in the *Journal of Membrane Science* in 2003 [60], is highlighted as one of the most influential papers in the field of feed spacers. This study is recognized for its substantial impact, being the top document in terms of GC (440) and GC per year (GCY_i) of 20 (**Figure 9 (A)**). The paper provides a detailed examination of heat and mass transfer mechanisms in DCMD, emphasizing the role of spacers in enhancing heat transfer. It reveals that while mass transfer's impact on heat transfer rates is minimal, spacers significantly improve heat transfer coefficients and mass fluxes, enhancing the overall efficiency of DCMD process. This influential work offers both theoretical advancements and practical insights into the optimization of feed spacers and their impact on MD.

When evaluating local citation (LC) metrics, the article titled "*Biofouling of Spiral-Wound Nanofiltration and Reverse Osmosis Membranes: A Feed Spacer Problem*" by Vrouwenvelder et al., published in 2009 in *Water Research* journal, stands out with 100 citations [134]. This study provides an in-depth analysis of biofouling in both full-scale and NF pilot-scale installations. The research highlights that, irrespective of permeate production rates, the presence of feed spacers significantly increases feed channel pressure drops and biomass concentration in NF systems. The findings underscore the crucial role of feed spacers in biofouling, demonstrating that biofouling is predominantly a feed spacer issue. This paper's extensive citation record reflects its significant contribution to understanding biofouling mechanisms and its influence on membrane performance. The LC/GC ratio was also examined to provide information about the scope of each article in the top 10 list shown in **Figure 9 (A)**. A high LC/GC ratio indicates that an article is highly specialized within the feed spacer domain, whereas a low LC/GC ratio suggests that the article has a broader, more global scope. The study with the highest LC/GC ratio (40.09) is by Koutsou et al. and published in 2007 [165], titled "*Direct Numerical Simulation of Flow in Feed Spacer-Filled Channels: Effect of Feed Spacer Geometrical Characteristics*". This study is significant for its detailed numerical and experimental analysis, which enhances the understanding of hydrodynamic and mass transport phenomena in spacer-filled membrane channels. Through direct numerical simulations of the Navier-Stokes equations in 3D geometries that closely mimic real-world spacer-filled channels, the study investigates the impact of feed spacer geometry on flow dynamics, including boundary layer development, vortex formation, shear stress distribution, and pressure drops. The insights gained are crucial for optimizing spacer design to improve mass transport and reduce fouling and CP in membrane systems. Conversely, the article titled "*Reverse*

Electrodialysis: A Validated Process Model for Design and Optimization” by Veerman J. et al. and published in 2011 [174], stands out with the lowest LC/GC ratio at 4.32, indicating a broader, more globally relevant scope. Despite this, it boasts the highest relative GC citations (RGC_i) value of 3.36, highlighting its significant impact on the wider scientific community. In this study, the authors developed and empirically validated a model for the RED process, focusing on optimizing system design. Their operational choices led to minimized risk of leakages and allowed the use of very thin membranes with high fluxes, coupled with effective spacer that offer low resistance.

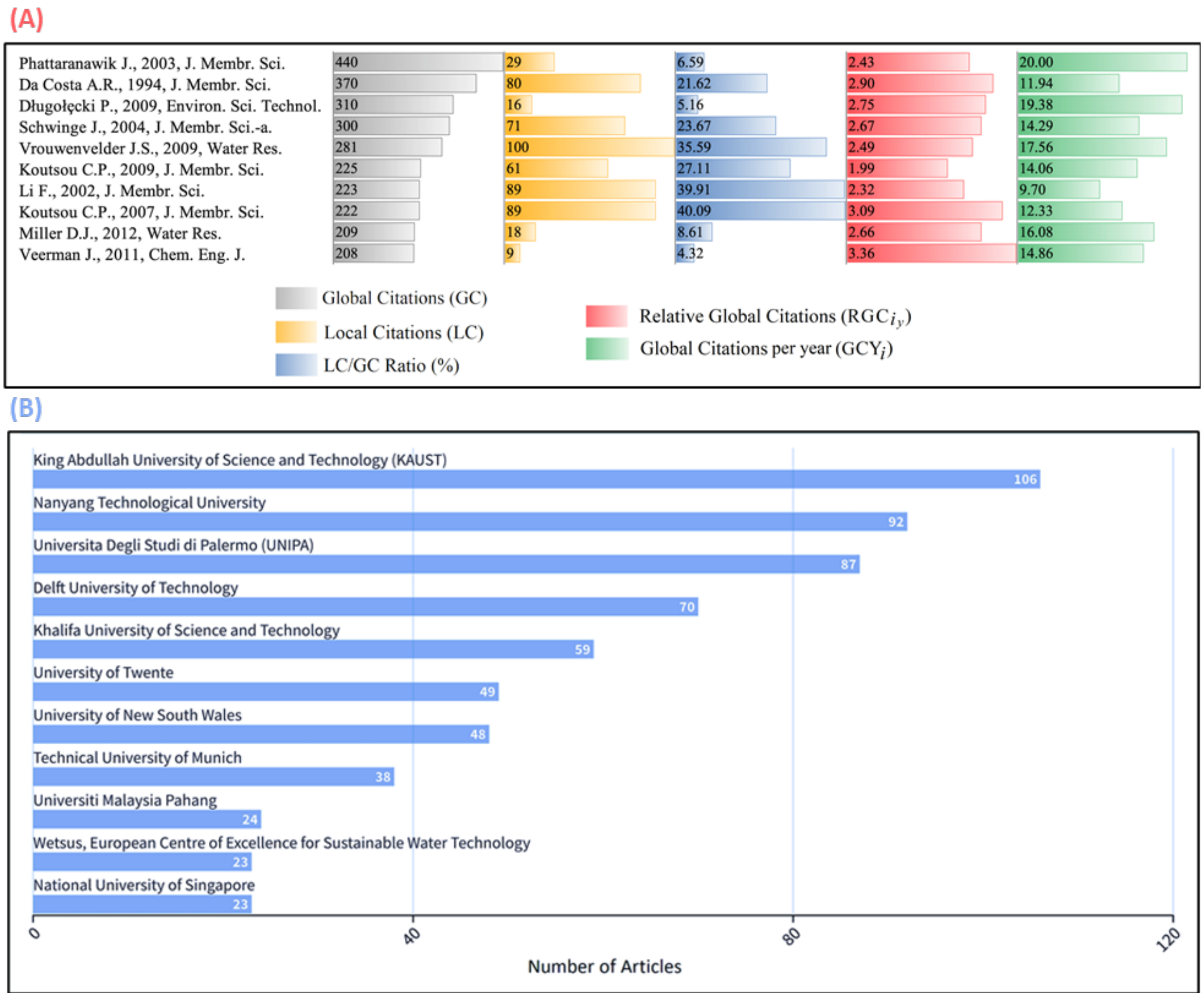

Figure 9. **(A)** Illustration of the top 10 articles, and **(B)** Top 10 affiliations of authors working on feed spacers development and evaluations in membrane processes.

Another bibliometric analysis of the collected feed spacer dataset was conducted to identify the top 10 affiliations of authors contributing to the development and evaluation of feed spacers in membrane processes and the results are shown in **Figure 9 (B)**. A significant volume of scientific research from an institution often reflects substantial financial support, which can drive considerable advancements in the field. Notably, there was a tie for the 10th position between Wetsus, European Center of Excellence for Sustainable Water Technology, and the National University of Singapore, with each contributing 23 articles; both institutions are therefore included in the figure. Additionally, it is important to clarify that the Biblioshiny program counts affiliations per author, meaning that if three authors from the same institution contribute to a single article, the Biblioshiny package counts this affiliation as three separate instances, not just one. When the results in **Figure 9 (B)** are examined, King Abdullah University of Science and Technology (KAUST) comes at the top of the list with a total contribution of 106. Nanyang Technological University comes 2nd with 9, and Universita Degli Studi di Palermo (UNIPA) 3rd with 87 articles.

Further analysis of the collected data on feed spacer research revealed regions leading advancements in this field and underscores the global collaboration and concentrated efforts driving its development, as illustrated in **Figure 10**. For clarity and ease of interpretation, the minimum number of documents per country was set at 15 in the figure. Furthermore, the size of each rectangle corresponds to the number of articles published by a given country. Colors represent distinct social clusters or network spaces, while the thickness of the connecting lines indicates the strength of collaborative publications.

It is clear that research conducted in the United States (US) on feed spacers development and evaluation is leading the field with a total publication output of 82 articles, followed by the Netherlands with 61 articles and Australia with 59 articles (**Figure 10**). The authors working from the US also showed the highest level of international collaboration, co-authoring 46 articles with researchers from 10 different countries, with the thickest link being between the US and Saudi Arabia (14 co-authored articles). Researchers from South Korea are the most recent contributors, with an average publication year of 2019.13, while articles from the Netherlands have the highest average citation count ($AGCD_{It}$) of 81.8. When adjusting for publication time, research carried out in Saudi Arabia stands out with the highest average number of citations per article ($ARGC_{It}$) of 1.74. Furthermore, the analysis revealed four country clusters, each consisting of 2 to 4 countries as shown in **Figure 10**. The blue cluster is the most recent, with an DAA_{It} of 2018.03, the orange cluster has the highest average global citations per document ($AGCD_{It}$) value of 54.47, and the green cluster leads in average relative global citations ($ARGC_{It}$) value of 1.24. Overall, the analysis underscores the vibrant and collaborative nature of global research in feed spacers domain, with leading contributions from specific countries and significant variations in research impact and publication trends.

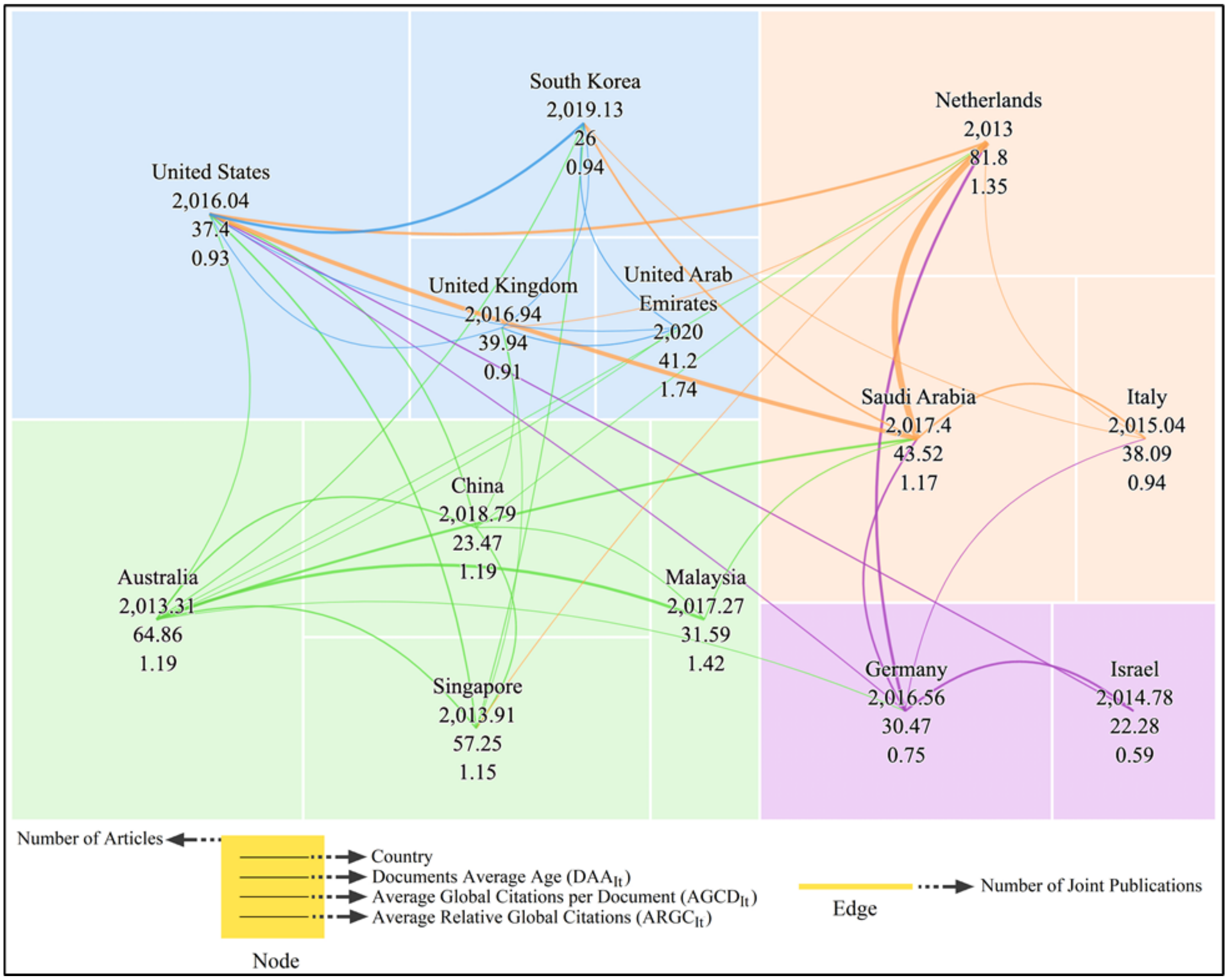

Figure 10. Co-authorship analysis of countries contributing to feed spacer development and evaluations (weights = documents, minimum number of documents of an author = 15, clusters with a single item are removed).

3.8 Text mining on titles and/or abstracts

This section looks into analyzing the development and evaluation of feed spacers in membrane processes through text mining, conducted on articles' titles and/or abstracts. In the collected dataset, one article did not have an abstract, therefore, the analysis was carried out on the remaining 456 articles. The results of such analysis in schematically illustrated in **Figure 11**.

Figure 11 (A) revealed that the majority of authors used between 115 to 230 words in their abstracts, with 318 articles' abstracts falling within this range. The average word count for abstracts in the dataset was approximately 202, with the shortest abstract containing 54 words and the longest one extended to 443 words. Furthermore, most abstracts had reading times between 10 to 20 seconds (329 articles), with an average reading time of 17.23 seconds as shown in **Figure 11 (A)**. The shortest reading time was 4.72 seconds, while the longest abstract required 37.42 seconds to read. Notably, the Python Textstat library calculates reading time based on characters rather than words, so the reading time scores of the abstracts did not directly correspond to word count.

Figure 11 (A) also illustrates the distribution of readability scores for the abstracts using the Flesch Reading Ease formula, with negative values adjusted to 0. Higher scores indicate easier-to-read material, while lower scores suggest more complex abstracts. The analysis showed that most abstracts fell into the "very difficult" (i.e., graduate level) and "difficult" (i.e., college level, 18-20-year-olds) categories, with 234 and 212 articles, respectively. This suggests that the abstracts often contain complex sentence structures and longer words, tailored for a more educated audience. These readability scores can be seen as both a strength and a limitation. On one hand, the complexity is appropriate given that the target audience consists of specialists in the feed spacers field. Moreover, if the goal was to make the research accessible to a broader audience, simplifying the abstracts might be necessary to enhance public understanding. However, this is not usually the case, as the field of feed spacer development and evaluation is primarily focused on pushing the boundaries of the field further. The research is often aimed at advancing the commercialization of such spacers or deepening the understanding of their role in membrane processes to optimize their performance. Therefore, the targeted audience is often experts in the field or scientists working on similar topics.

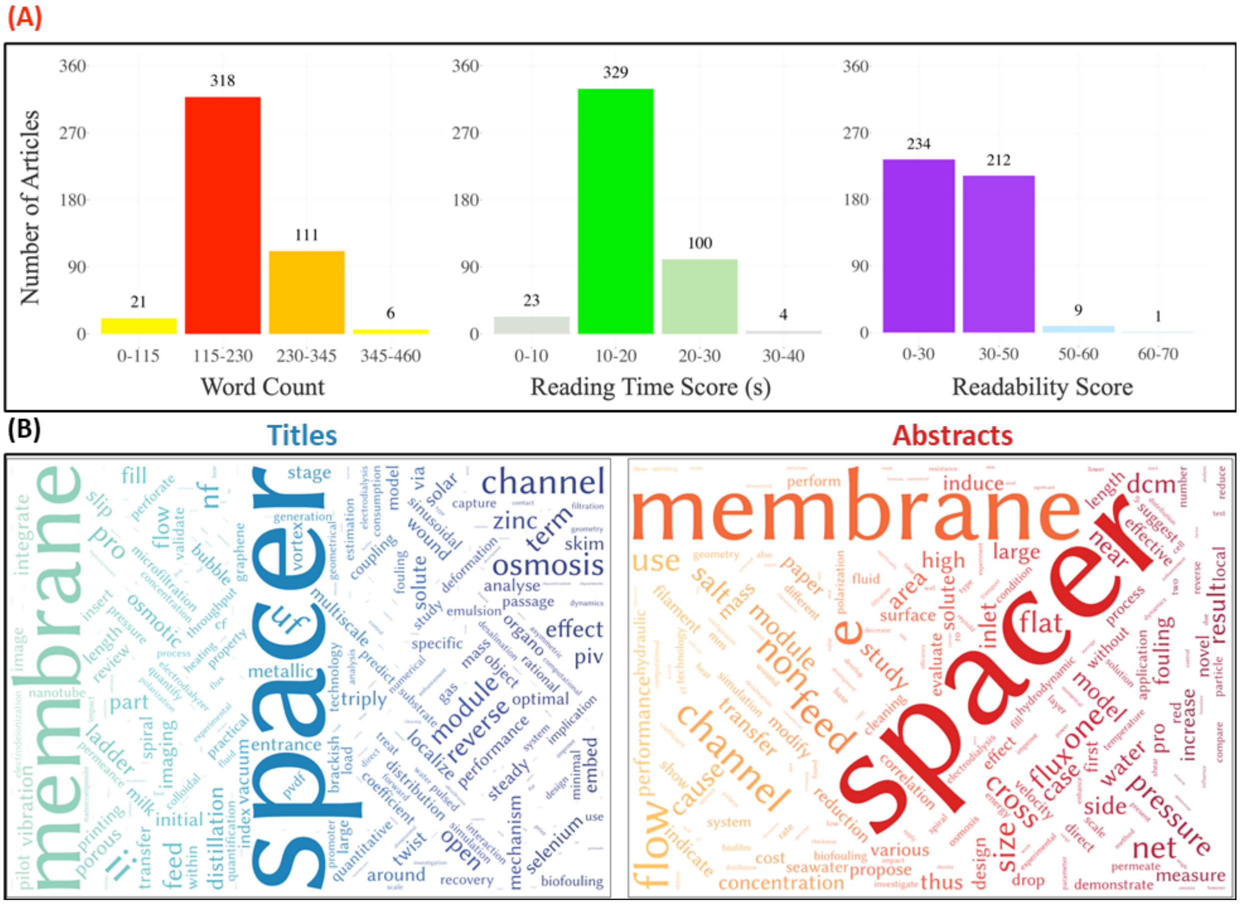

Figure 11. (A) Text mining analysis results showing word count, reading time score, and readability score, and **(B)** Word cloud of feed spacer-related articles' titles and abstracts.

The words "Spacer" (315) and "Membrane" (301) were the most common words in the titles as well as the abstracts "Spacer" (2178) and "Membrane" (1744) as shown in the word cloud depicted in **Figure 11 (B)**. The 3rd common word in the titles was "Channel" (111), followed by "Osmosis" (106), "Reverse" (85), and "Wound" (59). It is natural for the words "Spacer" and "Membrane" to dominate the titles and abstracts of such articles as they represent the core focus of the research. Interestingly, the frequent appearance of "Spacer" and "Membrane" indicates that these studies are highly specialized within the membrane technology field, focusing specifically on the role and impact of spacers within these systems. As for the words "Osmosis" and "Reverse" being common in titles suggest that a significant portion of the research is related to RO processes, where feed spacers are crucial in enhancing performance and reducing fouling. RO is a widely studied area in membrane technology, explaining the prominence of these terms. Furthermore, the appearance of "Channel" likely relates to the structural role of feed spacers in creating feed channels for fluid flow within membrane modules. This is a critical aspect of how spacers function, making it a key term. Additionally, when researchers conduct numerical simulations to understand or optimize specific feed spacer geometries, they often refer to the geometry under examination as a "spacer-filled channel" The term "Wound" typically refers to SWM modules or configurations, where feed spacers are a standard component. This indicates that a significant portion of the literature focuses on this specific type of membrane module, which is widely utilized in various membrane processes such as RO, NF, FO, and PRO.

Besides "Membrane" and "Spacers" words, the abstracts contained common words such as "Feed", "Channel", "Flow", "Mass", "Transfer", "Surface", Fouling", "Biofouling", "Flux", Design", "Concentration", "Polarization", "Reduction", "Pressure", "Evaluate", "Study", among others. The frequent occurrence of terms related to fluid dynamics, fouling, performance metrics, and design in the abstracts of feed spacer-related articles reveals a comprehensive research focus on optimizing membrane processes. Researchers are particularly concerned with how feed spacers impact flow patterns, mass transfer, and surface interactions, as well as their critical role in mitigating issues like fouling, biofouling, and CP. The emphasis on terms like "Flux" "Pressure" and "Reduction" highlights the ongoing efforts to enhance membrane performance metrics, while the recurring use of "Evaluate" and "Study" reflects the systematic analysis of various feed spacer designs and their effectiveness. Together, these findings underscore the pivotal role of feed spacer innovation in advancing the efficiency and sustainability of membrane technologies.

3.9 Language processing combined with ML analysis on abstracts

Sentiment, subjectivity, and emotion analyses, key methods in ML and NLP, were conducted on the abstracts of the articles to gain insight into the authors' research experiences, their perceptions of scientific processes, and their modes of expression. The results, based on dominant scores, are illustrated in **Figure 12**. Sentiment and subjectivity analyses were performed on 456 abstracts, while the emotion analysis, due to algorithmic limitations in processing data instances exceeding 512 tokens, was conducted on 450 entries. **Figure 12** revealed that the majority of authors expressed positive sentiments about their research outcomes. Specifically, 385 articles exhibited a dominant positive sentiment, 63 displayed negative sentiments, and 8 were neutral. Articles with negative sentiments typically indicate that the study results did not meet expectations or that the authors highlighted challenges, problems, or negative aspects related to feed spacers.

The subjectivity analysis shows that most abstracts (453 articles) are dominated by objective scores, suggesting that the authors primarily focus on presenting information in an unbiased manner, rather than expressing personal opinions or biases (**Figure 12**). In the emotion analysis, it was found that 4 articles conveyed an "approval" emotion, while the remaining 446 were categorized as "neutral". This lack of emotional tone is characteristic of scientific writing, where objectivity is often prioritized. However, the presence of "approval" in a few abstracts indicates that those articles positively evaluate or endorse a particular topic.

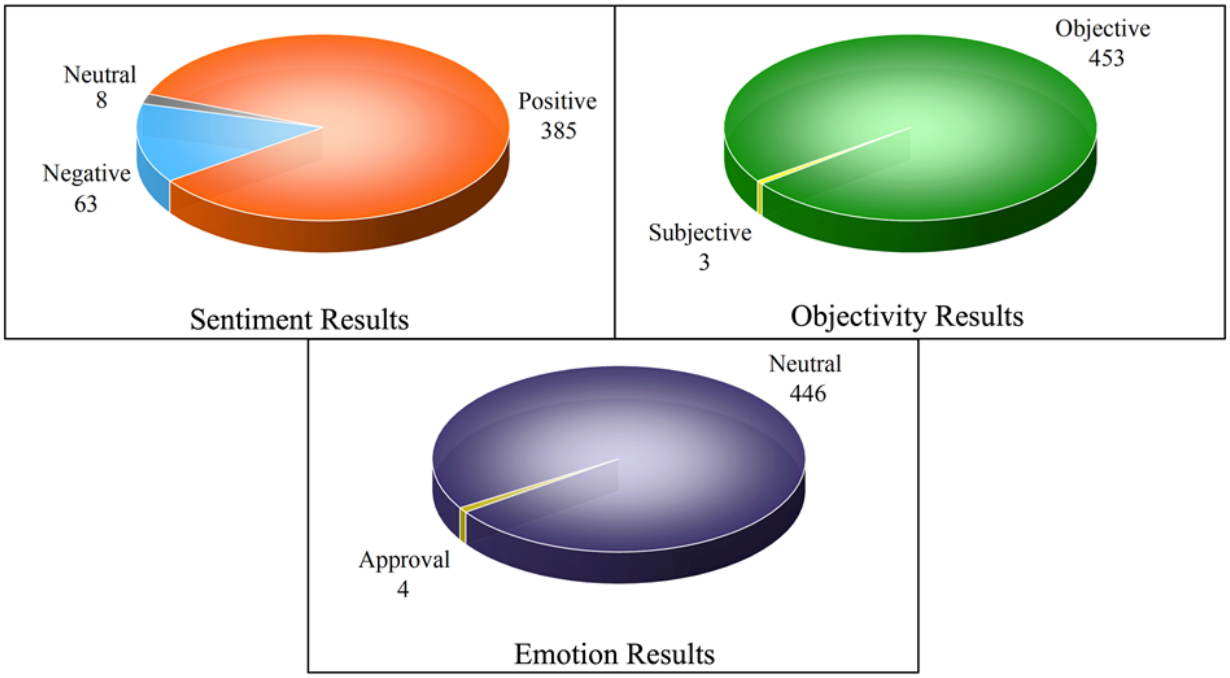

Figure 12. Results of the sentiment, subjectivity, and emotion analyses of the feed spacer-related articles' abstracts.

3.10 Conclusions

This study provided a comprehensive bibliometric and TM analysis of the feed spacer field in membrane processes, offering insights into the current state of research and identifying key trends and influential contributions. It analyzed research trends in feed spacer development, leading journals, key authors, and countries driving this research. The study also examined frequently studied parameters and challenges related to feed spacers, research distribution across membrane process types, various research methods, and insights into spacer types and fabrication techniques. The investigation revealed the prominent role of feed spacers in optimizing membrane performance by enhancing mass and heat transfer and reducing pressure drop. RO emerged as the most studied membrane process, with 153 articles. Significant attention was also given to MD, NF, and FO, with 76, 46, and 45 articles, respectively. This distribution underscores the critical importance of feed spacers in various membrane applications, particularly in SWM commonly used for these processes.

The analysis also highlighted a strong preference for experimental research, with 231 studies focusing exclusively on experimental evaluations of feed spacers in membrane processes. Numerical simulations, although less common with 103 studies, have proven valuable for validating results and refining empirical models. Theoretical research, particularly through CFD, provided detailed insights into fluid dynamics and spacer performance, enabling the optimization of spacer geometries. Combining experimental and theoretical methods offers a comprehensive understanding of spacer behavior, leading to advancements in spacer design and membrane process optimization.

Research on feed spacers predominantly focuses on three critical parameters: mass transfer, heat transfer, and pressure drop, crucial for optimizing membrane processes. Studies frequently investigate how spacer geometry influences these parameters, with mass transfer and pressure drop being the most commonly examined. Enhanced mass transfer typically results from improved spacer performance in generating turbulence and fluid mixing, thereby increasing membrane efficiency. Heat transfer, though less frequently studied, is vital in processes like MD, where thermal management is key. Pressure drop is closely linked to energy consumption, making it a significant consideration in pressure-driven processes. Additionally, fouling, biofouling, wetting, and scaling present operational challenges, often compromising system efficiency and longevity. Feed spacers mitigate these issues by promoting turbulence and fluid mixing, which reduces foulant deposition and disrupts biofilm formation. However, some spacer designs may inadvertently exacerbate fouling, indicating the need for optimized geometries.

Commercial feed spacers dominate the research landscape, with 178 articles focusing on these designs due to their accessibility and ease of use. However, engineered spacers, particularly 3D-printed designs, are gaining attention for their potential to optimize membrane performance. These spacers offer unparalleled precision and the ability to create complex geometries that enhance fluid dynamics and reduce fouling. The growing trend toward 3D printing in spacer fabrication reflects its advantages, making it a promising area for future research and development.

The analysis also identified key journals, leading authors, and their collaborations, offering valuable insights for researchers. The *Journal of Membrane Science* and *Desalination* Journal emerged as the most influential publishers, with the former dominating in articles published, citations, and indices. Among authors, *Vrouwenvelder J. S.* led in publication volume and impact, with significant contributions also from *Fane A. G.* and *Ghaffour N.* Collaborative networks revealed five primary clusters with strong connections between key researchers, reflecting a robust research community. Pivotal studies, such as *Phattaranawik et al.'s* 2003 work on heat transport in membrane distillation and *Vrouwenvelder et al.'s* 2009 exploration of biofouling, have significantly shaped the field.

Lastly, machine learning analysis of abstracts provided insights into authors' perspectives and the overall tone of research. Sentiment analysis revealed that most abstracts expressed positive sentiments, with 385 out of 456 articles showing dominant positive sentiments, reflecting satisfaction with research outcomes. Overall, this study underscored the importance of continued innovation and collaboration in feed spacer research, emphasizing the need for ongoing investigation into design optimization, material advancements, and performance evaluation to enhance the efficiency and sustainability of membrane processes.

3.11 Future directions and recommendations

Feed spacers have been extensively studied in processes like RO, MD, and NF for many years. However, their role in processes such as PRO, MBR, and CDI remains a relatively less explored area. Future research should focus on refining spacer designs for these applications to enhance performance and gain more insights into their impact on the process. Generally, feed spacers are optimized for particular processes; for instance, in RO, the design focuses on maximizing mass transport while minimizing pressure drop and fouling. In contrast, the optimization for feed spacers in CDI emphasizes effective ion transport and improved mass transfer between the electrodes. Given the unique requirements of other membrane processes (i.e., other than RO), along with the limited research in these areas, more studies are needed to explore and refine feed spacer designs that can significantly enhance performance in these applications.

Furthermore, numerous studies on feed spacers continue to primarily depend on experimental methods, despite the extensive availability of fluid simulation software. This trend highlights a missed opportunity, as simulations of feed spacers in membrane processes are not particularly complex and can provide valuable insights. Therefore, future research should aim to combine experimental approaches with numerical simulations, fostering a more holistic understanding of spacer performance and optimizing them for specific membrane processes.

The role of feed spacers in affecting critical parameters in membrane processes, such as mass transfer, heat transfer, and pressure drop, can be better understood when adopting a holistic approach that integrates both experimental and numerical methods. Future research should continue to prioritize the development of advanced feed spacer designs that enhance fluid dynamics while minimizing pressure drop. This entails exploring innovative materials and geometries, such as 3D-printed structures or coatings with anti-fouling properties, to further mitigate fouling, scaling, and biofouling challenges. Additionally, the interplay between these parameters needs careful consideration, as well as their collective impact on overall membrane performance and energy efficiency. Collaborative efforts across disciplines are essential to elucidate the complex interactions that govern membrane behavior in the presence of feed spacers.

With the widespread adoption of 3D printing technologies, researchers are increasingly recognizing the superior performance characteristics of 3D-printed feed spacers compared to their commercial counterparts. Thus, the focus of future research should primarily revolve around leveraging these advanced manufacturing methods to develop innovative spacer designs that enhance membrane processes. Notably, 3D printing offers unique advantages, such as the ability to fabricate complex geometries that optimize fluid dynamics and reduce fouling, both critical aspects for improving membrane efficiency. Furthermore, exploring the potential for in-situ fabrication of spacers directly on membrane surfaces could represent a transformative step in the field. This approach has the potential to streamline manufacturing processes and minimize material waste, leading to substantial cost savings.

Despite these advancements, a significant gap exists in research regarding the production costs of both commercially available and 3D-printed feed spacers. Understanding the economic implications of different fabrication methods is essential for advancing the commercialization of innovative spacer designs. A comprehensive study comparing the costs associated with producing feed spacers on both commercial scales and through 3D printing would provide valuable insights into the most cost-effective approaches while also informing the design process. Researchers must investigate cost-effective materials and processes that maintain performance without compromising affordability. Moreover, while many of the new 3D-printed spacer designs exhibit promising performance improvements, their practical implementation on a commercial scale presents challenges. Complex geometries or sharp edges inherent in certain 3D-printed spacers can potentially damage membrane surfaces, compromising the longevity and efficiency of membrane systems. Thus, it is crucial for researchers to consider the practicality of these innovative spacers during the optimization process, ensuring that new designs are effective in laboratory settings and also viable for real-world applications. By addressing these challenges and fostering collaboration between researchers and industry practitioners, the future of feed spacer research can drive significant advancements in membrane technology, ultimately leading to more efficient and sustainable water treatment solutions.

3.12 Acknowledgement

This publication is part of project PID2022-138389OB-C31, funded by MCIN/AEI/10.13039/501100011033/FEDER, UE. This work was supported by the NYUAD Water Research Center, funded by Tamkeen under the NYUAD Research Institute Award (Project CG007).

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