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Unveiling the future of graphene oxide-based desalination membranes: Bibliometric analysis, AI-powered topic modeling and research evolution forecast, patent analysis, and regional feasibility in South Asia

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ABSTRACT

The current world requires us to examine water scarcity as a vital matter. The main problem with water usability stems from its high salt content, which makes it unsuitable for different applications. The world now witnesses an increasing adoption of membrane-based desalination technology for water treatment. This study is based on a comprehensive evaluation of graphene oxide (GO)-based membranes for desalination operations. A complete bibliometric evaluation of research progress in GO-based membranes for desalination required a Scopus database download of a comprehensive dataset. The research hotspots become visible through Burst keyword analysis. The database underwent topic modeling and research evolution prediction through the integration of AI-derived models. The analysis of patent data from the "Lens" database enabled researchers to study actual GO-based membrane applications for desalination and their technological advancements. The study assesses industrialization challenges of GO-based membranes for desalination, along with a feasibility assessment to determine the implementation potential of GO-based membranes for desalination in South Asia, where water shortages and saltwater salinity present significant challenges. The research provides essential information to scientists who want to study GO-based membranes for desalination and business leaders who need to evaluate the current state and operational viability of this technology.

Introduction

The world faces increasing water supply problems because urban growth, industrial development, and population expansion have led to higher water usage needs. The combination of water pollution with organic and inorganic pollutants poses a critical issue that damages human health and wildlife populations. Seawater desalination is a critical method for producing drinking water, providing essential resources to coastal regions and arid zones. However, existing water desalination methods, whether thermal or membrane-based, have considerable operational difficulties principally linked to elevated costs resulting from scaling and fouling [1]. The elimination of divalent ions, including calcium, magnesium, and sulfate, is crucial for increasing the efficacy of thermal seawater desalination facilities [2,3]. The desalination industry uses Nanofiltration (NF) as a standard pretreatment method because it effectively removes scale-forming divalent ions through its high rejection performance [4]. It has been a constant effort to find and investigate a new material for membrane manufacturing that improves selectivity, permeability, fouling resistance, and chemical stability simultaneously [5]. Membrane-based technologies have gained popularity in water treatment and chemical purification due to their ability to achieve excellent separation results with a low environmental impact [6,7].

Graphene oxide (GO), a two-dimensional (2D) material and an oxidized derivative of graphene, has garnered significant attention as a promising material for membrane technology due to its remarkable properties [8]. The material features a unique pore structure and chemical stability, together with enhanced mechanical properties, chemical resistance, and molecular filtration ability [9,10]. The nanochannel dimensions of GO-based membranes determine which molecules can pass through based on their size. Due to the hydrophilic

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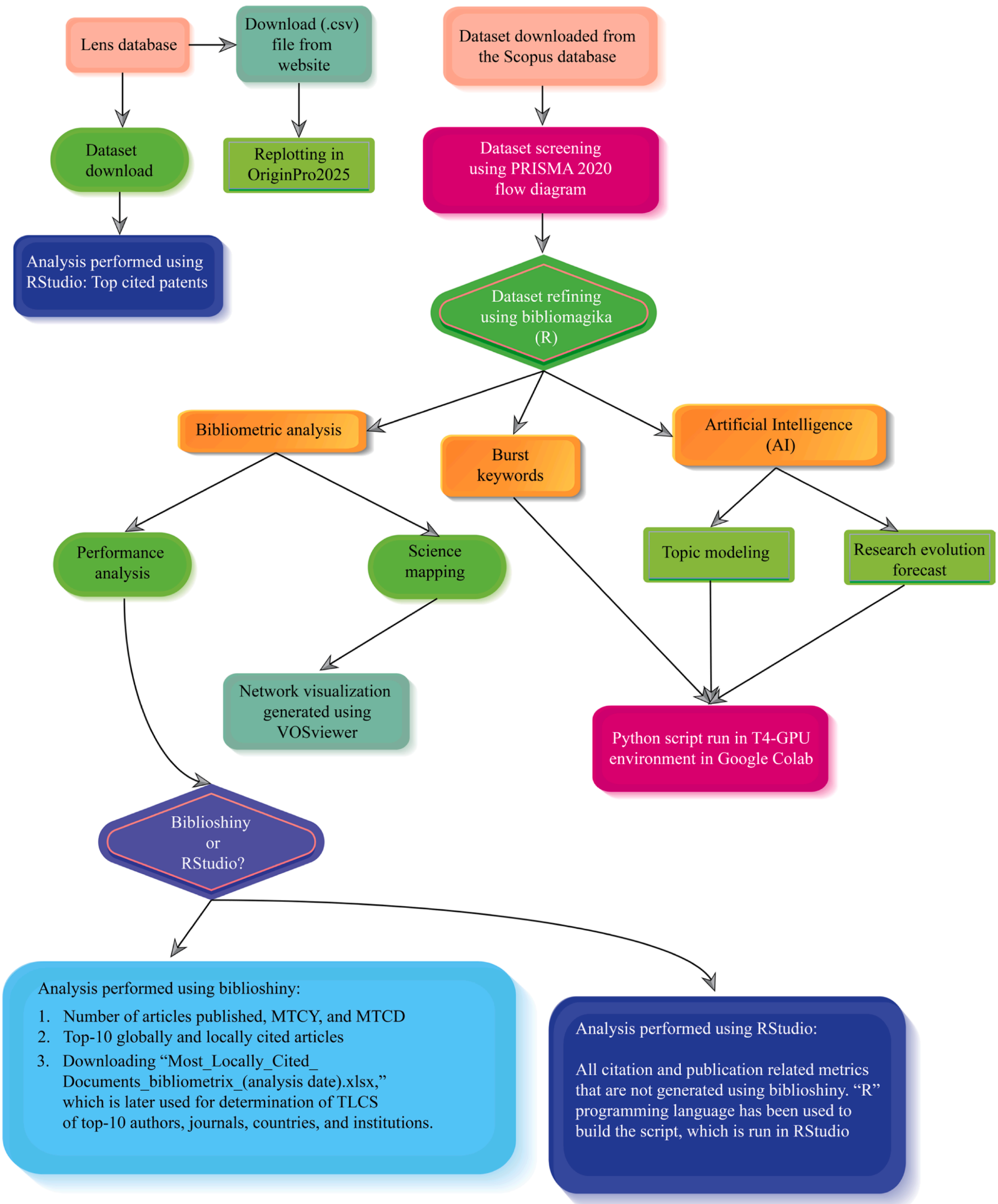

Fig. 1. A brief overview of the methodological pipeline.

characteristics of GO-based membranes, they are susceptible to swelling upon exposure to water and elevated humidity during filtration. Membrane re-exfoliation and delamination make the use of these materials in aqueous solutions impractical [11,12]. The presence of hydroxyl, epoxy, and carboxyl groups on the basal planes and edges of GO enables the modification and production of membranes [13]. Graphene oxide exists as a nanomaterial that contains sp^3 hybridized oxidized sections and unaltered sp^2 regions and has become one of the most widely used nanomaterials. The membrane fabrication process for nanofiltration, pervaporation, and desalination applications has gained substantial interest because of its unique water channels and selective permeation characteristics [14–17]. The frictionless flow of water through graphene sheet channels occurs because of monolayer flow and well-mixed fluid states that minimize resistance [18]. Water molecules in nanoconfined spaces between graphene layers experience an arrangement that leads to increased permeability [19]. Nanocapillaries within GO membranes allow frictionless water passage while blocking other molecules through steric hindrance [20]. Various chemicals and techniques have modified GO to control the pore structure. The combination of graphene oxide with polymers yields flexible membranes that allow water to pass through at a higher rate. The addition of nanomaterials, including metal-organic frameworks (MOFs) and nanotubes, to intercalation procedures enhances both desalination efficiency and water permeation rates [21–23].

Bibliometric analysis employs statistical methods to examine books, papers, and other published works, aiming to understand how research fields evolve and gain influence. The method is widely used to study the structure and operational patterns of scientific research [24]. The most popular databases for bibliometric analysis include Scopus, Web of Science, Google Scholar, and Publish or Perish. Artificial Intelligence (AI) collaborates with bibliometric analysis and topic modeling to examine research patterns and thematic groupings in scientific literature [25]. Patents help create the technological framework that describes both the current state and future development possibilities of a particular field [26]. To identify and present a real-world scenario, analyzing patents is often important, alongside analyzing research articles.

Desalination is essential for South Asian nations, mostly due to widespread water scarcity resulting from declining supplies, pollution, and excessive groundwater extraction [27,28]. This scarcity gets worse by rapid population growth, which heightens demand, and climate change, which induces unpredictable rainfall and droughts [29]. Moreover, geographical constraints in coastal regions, where freshwater is limited despite being near to the sea, highlight desalination as a viable solution [30]. Desalination faces hurdles, including substantial initial and operational costs, high energy use, environmental consequences from brine and marine impact, and the need for advanced technology and expertise [31–33]. GO-based membrane filtration resolves several feasibility issues in water because studies indicate that graphene oxide membranes are up to three times more permeable than conventional RO membranes. It can lower desalination energy demand by 15–46 %, resulting in approximately 7–8 % cost savings in large-scale plants [34]. The energy consumption of GO membranes amounts to 2.3–2.5 kWh/m^3, which is lower than traditional reverse osmosis systems at 4.5 kWh/m^3, thus making them suitable [35]. New materials entering the existing systems must undergo complete regulatory approval before implementation. The testing process for safety and efficacy runs long, which extends the time needed for their implementation [36].

The global body of research on GO is vast and highly diverse in focus. However, limited information channels and complex variables make it difficult to identify underlying patterns—a situation that may contribute to fragmented research directions and hinder the practical application of GO nanofiltration membranes. To address this challenge, we employ bibliometric analysis and AI-driven forecasting to observe and analyze the development trends of GO membranes from a macro-level perspective.

This study uses an integrated methodology that includes bibliometric analysis, burst keyword detection, AI-powered topic modeling, patent analysis, and regional feasibility assessment. While burst keyword and AI-driven topic modeling identified changing research hotspots and predicted future trends, bibliometric performance analysis and science mapping were used to assess research productivity, citation impact, and connections among influential studies. The technological developments, innovation dynamics, and commercialization pathways of GO membranes were uncovered through patent analysis conducted using the Lens database. When combined, these methods produce a data-driven framework that connects basic research findings with current trends in practical applications. The potential of GO membranes to mitigate South Asia's acute water shortage is further contextualized by the inclusion of a regional feasibility assessment. By integrating quantitative bibliometrics with AI and patent intelligence, the study delivers a holistic perspective. Ultimately, it facilitates informed decision-making for researchers, policymakers, and industry leaders, establishing this work as a distinctive contribution to the advancement of sustainable desalination technologies.

Table 1
Main information (overview) of the investigated dataset on 'Graphene oxide-based membrane for desalination' from 2013 to 2024.

Parameter	Value
Sources	117
Number of articles	382
Annual growth rate (%)	32.26
Document average age (DAA)	4.26
Average citations per article	50.41
References	16,713
Keywords Plus (ID)	795
Author's Keywords (DE)	2968
Authors	1747
Authors of single-authored docs	5
Single-authored docs	5
Co-Authors per Document	5.68

Methodology

Two datasets were used for analysis in this study: one was downloaded from the Scopus database, and the other was downloaded from the Lens database. A brief explanation of the search query used to download the dataset from the Scopus database and the Lens database, along with the strategy for screening and refining the dataset, is provided in **Supplementary Document 1.** Dataset from the Scopus database is analyzed using "R" scripts and Biblioshiny to understand research progress. The number of articles, MTCD, and MTCY —top-10 globally cited articles and top-10 locally cited articles — are analyzed using Biblioshiny. The rest of the analysis is performed using "R" scripts in RStudio. The method of determining TLCS and average TLCS for authors, journals, institutions, and countries requires a specific procedure, which is explained in **Supplementary Document 2.** The network visualizations for science mapping have been performed using VOSviewer. Burst keywords (trigrams), topic modeling, and research evolution forecast were performed using the Python script in Google Colab (T4-GPU environment). Dataset from the Lens database has been downloaded to determine top cited patents (both cited by patents and cited by all articles) using an "R" script in RStudio, and the rest of the results were generated by downloading a comma-separated value (.csv) file from the website and replotting it in OriginPro2025. The "R" scripts and Python scripts employed in this study are included as part of the supplementary information. Definitions of different metrics used in this study are provided in **Supplementary Document 3.** A brief overview of how different tools fit into the methodological pipeline is plotted in Fig. 1.

Result and discussion

Research progress on GO-based membranes for desalination

Bibliometric analysis

Articles

From the Overview (main information) section of the Biblioshiny web portal, the gathered information is summarized in Table 1.

From the table, it is evident that this is a vibrant and rapidly expanding field, with 382 documents, a 32.26 % annual growth rate, and an average document age of 4.26 years, indicating recent and dynamic research activity. The high average citations per document (50.41) and 16,713 references suggest significant influence and a well-connected literature base, while 1747 authors and a 5.68 co-authors per document ratio highlight extensive collaboration. The low number of single-authored documents (5) reflects a shift toward teamwork. With 2968 authors' keywords and 795 Keywords Plus, the research spans a broad scope, potentially signaling future opportunities for funding and leadership, though a focus on key themes may prevent fragmentation as the field evolves.

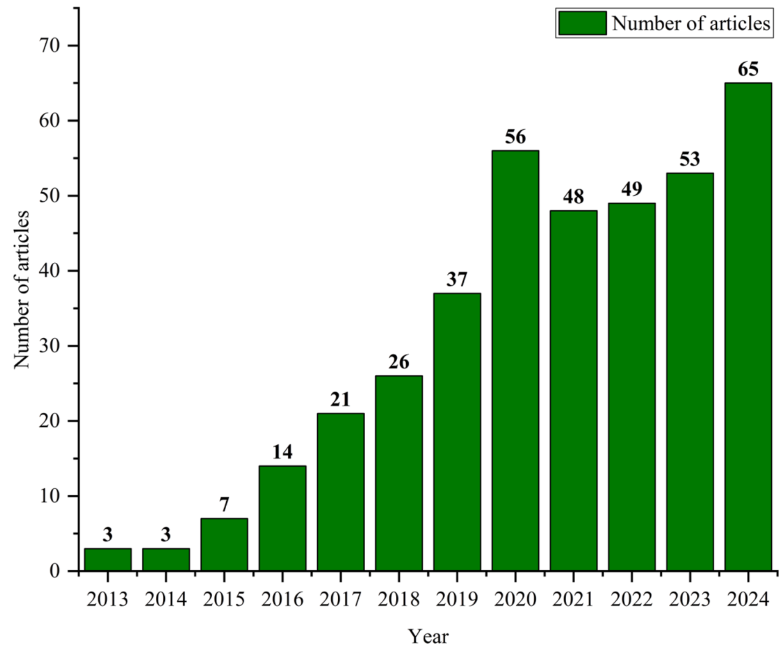

Fig. 2. Number of articles published over the years on GO-based membranes for desalination.

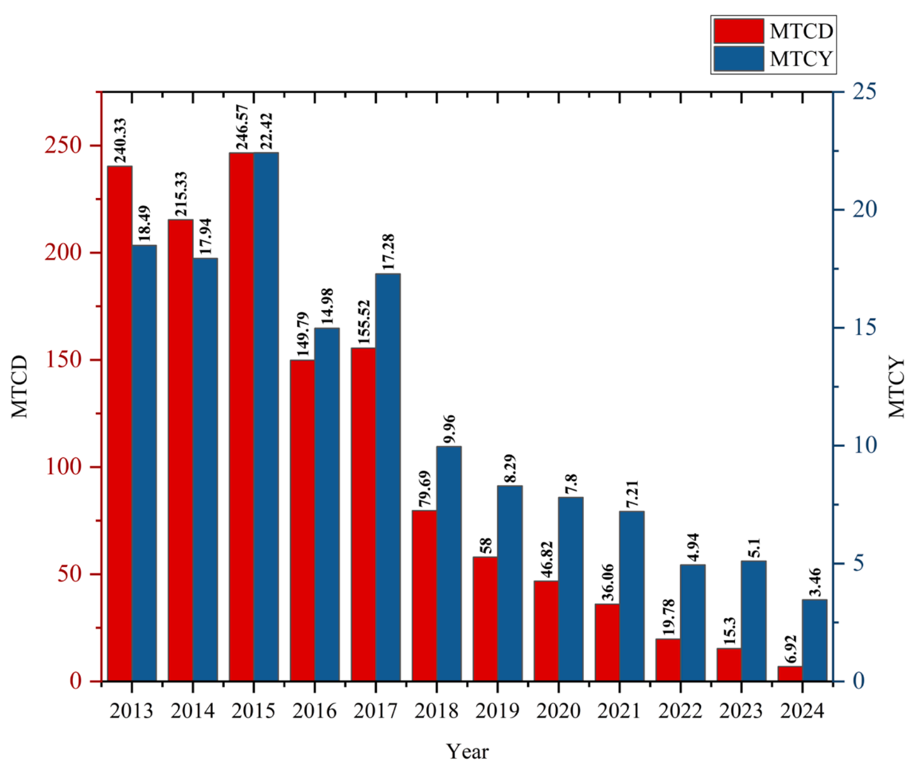

Fig. 3. MTCD and MTCY of the articles on GO-based membranes for desalination.

The number of articles published over the years is plotted in Fig. 2.

The graph shows a steady increase in the number of articles published on graphene oxide-based membranes for desalination and wastewater treatment from 2013 to 2024, starting at 3 articles in 2013 and peaking at 65 in 2024. The trend indicates a significant rise in research interest, with a notable acceleration after 2017, as the number of articles grew from 21 to over 50 in subsequent years. This suggests growing scientific attention and potential advancements in the field over the decade.

The mean total citations per document (MTCD) and mean total citations per year (MTCY) of articles in our dataset on the investigated topic are plotted in Fig. 3.

The bar chart illustrates the citation trends for Mean Total Citation per Document (MTCD) and Mean Total Citation per Year (MTCY) from 2013 to 2024, using data from a table. The notable rise in 2015, where MTCD peaked at 246.57 and MTCY at 22.42, could be attributed to a significant publication or a cluster of highly cited documents released around that time, possibly due to groundbreaking research or increased

Table 2
Top-10 articles (in terms of TGCS) and their TGCS, key findings, and references.

TGCS	Key Findings	Reference
1554	This study tackled the complex construction of homogeneous graphene oxide membranes, including precisely defined sub-nanometer pores for efficient ion sieving, redirecting the emphasis from water–ion flux to water–ion selectivity. The thorough investigation of ion penetration in GO films with regulated interlayer spacing demonstrated that ion transport is thermally activated by dehydration energy barriers, while water transport is predominantly unaffected. Moreover, the integration of graphene flakes demonstrated the ability to prevent membrane swelling and increase salt rejection, thus enhancing total desalination efficacy.	[37]
523	This study addressed the significant issue of membrane durability, emphasizing resistance to fouling and tolerance to chlorine while maintaining reverse osmosis efficiency. A double-action layer-by-layer (LbL) graphene oxide covering was developed on polyamide membranes, enhancing surface hydrophilicity, decreasing roughness, and significantly improving resistance to chlorine-induced degradation.	[38]
496	This study tackles the limitations of low water flux and fouling in polyamide nanofiltration membranes by producing graphene oxide-loaded polyamide membranes by interfacial polymerization. The integration of GO enhanced surface hydrophilicity and decreased roughness, leading to a twelve-fold increase in water flux while preserving excellent salt rejection efficacy.	[39]
479	Enhanced water permeability and hydrophilicity were attained by incorporating graphene oxide by in situ interfacial polymerization, wherein the interlayer spacing of GO served as an efficient water channel. The resultant GO-embedded polyamide thin-film nanocomposite membranes exhibited markedly improved water transport efficiency while maintaining selectivity.	[40]
418	The researchers created a distinct thin-film nanocomposite reverse osmosis (TFN-RO) membrane through the combination of rGO/TiO_2 nanocomposite, which delivered enhanced water permeability, salt rejection, antifouling properties, and chlorine tolerance. The modified membranes maintained their performance well after chlorination treatment, experiencing only a 3 % reduction in function, which made them suitable for extended desalination operations.	[41]
357	Researchers investigated selective ion transport through graphene oxide-based artificial biological channels to determine the impact of cation-π interactions and desolvation effects on this process. The research showed that cation penetration depends on temperature, while the combination of these forces controls the process, which provides a new understanding of ion selection in GO membranes.	[42]
301	Documented a simple nanomorphology composite for solar water disinfection. The photothermal shell of engineered rGO/MWCNTs features a rough, porous structure, which enhances solar energy collection and accelerates water movement and evaporation.	[43]
261	The interfacial polymerization process enabled graphene oxide to bond with polyamide through hydrogen bonding, producing membranes that exhibited superior flux rates, mechanical strength, and better fouling resistance and chlorine tolerance. The grafting method achieved better membrane performance and longer operational stability, which proved that GO integration creates durable desalination membranes.	[44]
244	Graphene oxide/polyacrylonitrile (GO/PAN) membranes featuring designed two-dimensional nanochannels were fabricated for high-salinity desalination. The membranes demonstrated outstanding performance, characterized by their high water transport efficiency and the ability to block 99.8 % of salt at 100,000 ppm salinity levels, making them suitable for harsh desalination processes.	[45]
239	The study provides a molecular-level understanding of rGO membranes, enabling the development of systematic separation methods. The researchers employed molecular dynamics simulations to correlate synthesis parameters with nanopore defect dimensions, allowing them to control water transport through size adjustments for enhanced membrane performance.	[46]

Table 3
Top-10 articles (in terms of TLCS), their key findings, and references.

TLCS	Key Findings	Reference
57	Ranked 1st in terms of TGCS (1554), and hence discussed earlier.	[37]
48	Ranked 2nd in terms of TGCS (523), and hence discussed earlier.	[38]
43	Ranked 4th in terms of TGCS (479), and hence discussed earlier.	[40]
34	Ranked 9th in terms of TGCS (244), and hence discussed earlier.	[45]
33	Ranked 3rd in terms of TGCS (496), and hence discussed earlier.	[39]
30	A new binder technique was employed to tackle the stability difficulty of graphene oxide membranes. The researchers created PDA-conjugated GO membranes on α-Al_2O_3 substrates, which achieved more than 99.7 % ion rejection while maintaining stable operation for 336 h.	[47]
29	The water permeability of reduced nitrogen-doped porous graphene oxide (rNPGO) membranes increased through the formation of nanoporous structures achieved by H_2O_2-assisted nanopore development. The method delivered water flux rates that were 26 times greater than those of traditional methods, while preserving salt separation efficiency.	[48]
28	Also ranked 8th in terms of TGCS (261), and hence discussed earlier.	[44]
25	Different surface modification techniques of graphene oxide lead to enhanced membrane functionality. The GO—COOH membrane fabrication process, achieved through pressure-assisted self-assembly, produced membranes with 20 % improved water permeability and 91.3 % Na_2SO_4 rejection.	[49]
25	The polyamide membranes exhibited improved water permeability and antibacterial properties after the addition of 0.12 wt % graphene oxide to their composition. The modified membranes demonstrated an 80 % improvement in water permeation.	[50]

academic attention. This spike suggests a temporary surge in influence, potentially driven by external factors like policy changes, funding, or a major scientific breakthrough. However, the subsequent decline in both MTCD and MTCY from 2016 onwards (e.g., MTCD dropping to 149.79 and MTCY to 14.98) indicates a possible reduction in citation impact, which might result from fewer impactful publications, a shift in research focus, or an aging document pool with fewer new citations. The consistent downward trend through 2024 (MTCD at 6.92 and MTCY at 3.46) could reflect a natural decay in citation rates as documents age, with newer works receiving less attention over time, or a dilution of impact due to increased publication volume. The decrease in citable years (from 13 in 2013 to 2 in 2024) also contributes, as fewer years of citation accumulation lower both metrics. Looking to the future, if this trend continues, citation rates may stabilize at a low baseline unless new high-impact research emerges, though predicting exact values requires more data.

The top-10 globally cited articles key findings, TGCS value, and references are summarized in Table 2.

The top-10 locally cited articles key findings, TLCS value, and references are summarized in Table 3.

For science mapping, citaion analysis based on unit of analysis articles has been performed. The resultant network is plotted in Fig. 4. The minimum number of citations of a document: 5 is set as the threshold.

From the VOSviewer data, 257 articles have been presented in the network visualization, with 21 clusters and a total of 803 links. The results indicate a good interrelationship between the articles in terms of citing each other. From the network visualization, we can observe that there are many thicker and thinner lines connecting the nodes, and the clusters (in which the nodes reside) are separated by a distinguished color. The lines indicate the tendency of articles to cite each other locally, and the thickness indicates the value of local citations. The larger circles indicate documents with higher global citation, and the infinitesimal distance between the nodes (articles) indicates they are

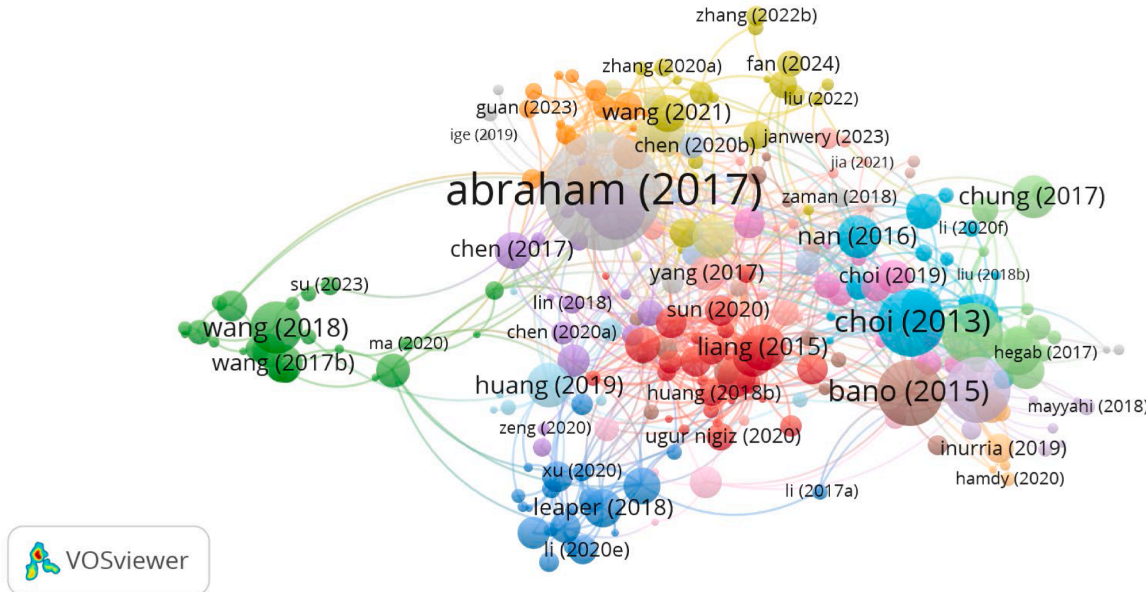

Fig. 4. Citation analysis (unit of analysis articles) on GO-based membranes for desalination applications.

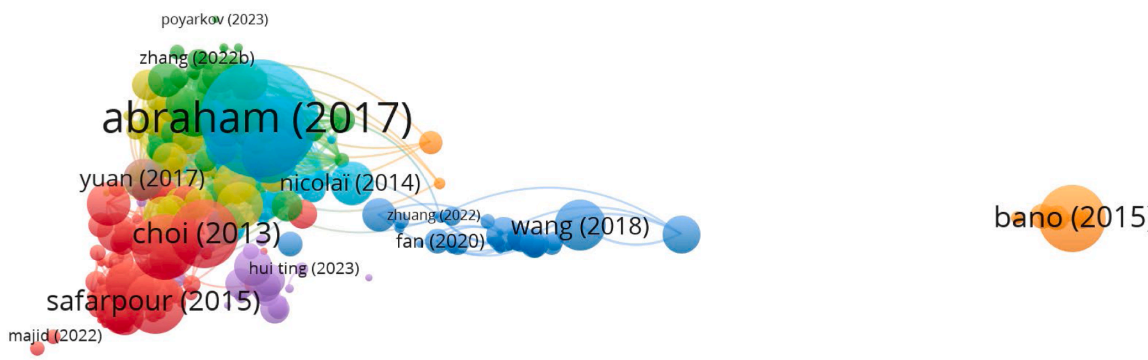

Fig. 5. Bibliographic coupling (unit of analysis articles) on GO-based membranes for desalination applications.

Table 4
Top-10 authors (in terms of number of publication) and their different metrics.

Author	Articles fractionalized	Publications	Percentage contribution (%)	h-index	g-index	i10-index	R-index	Q-index	m-index	TGCS	TLCS	Average TLCS per article
Chen Liang (23,049,099,400)	0.98	6	1.57	5	6	4	14.83	8.61	1.25	89	0	0
Huang Aisheng (7402,307,094)	1.95	6	1.57	6	6	6	119.5	26.78	0.67	717	103	17.17
Matsuya Ma, Hideto (57,201,543,303)	0.75	6	1.57	5	6	5	38.5	13.87	1	231	7	1.17
Zhang Xiwang (10,540,976,100)	0.78	6	1.57	6	6	6	73.5	21	0.75	441	52	8.67
Guan Kecheng (56,763,567,800)	0.62	5	1.31	4	5	4	32.2	11.349	0.8	161	7	1.4
Jin Wanqin (7402,071,332)	0.59	5	1.31	5	5	5	56	16.73	1	280	0	0
Kim In S. (7404,143,637)	0.84	5	1.31	4	5	3	45.6	13.51	0.5	228	21	4.2
Liang Shanshan (57,201,942,328)	0.78	5	1.31	4	5	3	14.8	7.69	1	74	0	0
Quan Xie (55,533,618,700)	1.01	5	1.31	5	5	5	64	17.89	0.71	320	19	3.8
Wang Huanting (8393,378,100)	0.60	5	1.31	5	5	5	73.4	19.16	0.42	367	29	5.8

Fig. 6. Co-authorship network visualization (based on unit of analysis authors) on GO-based membranes for desalination applications.

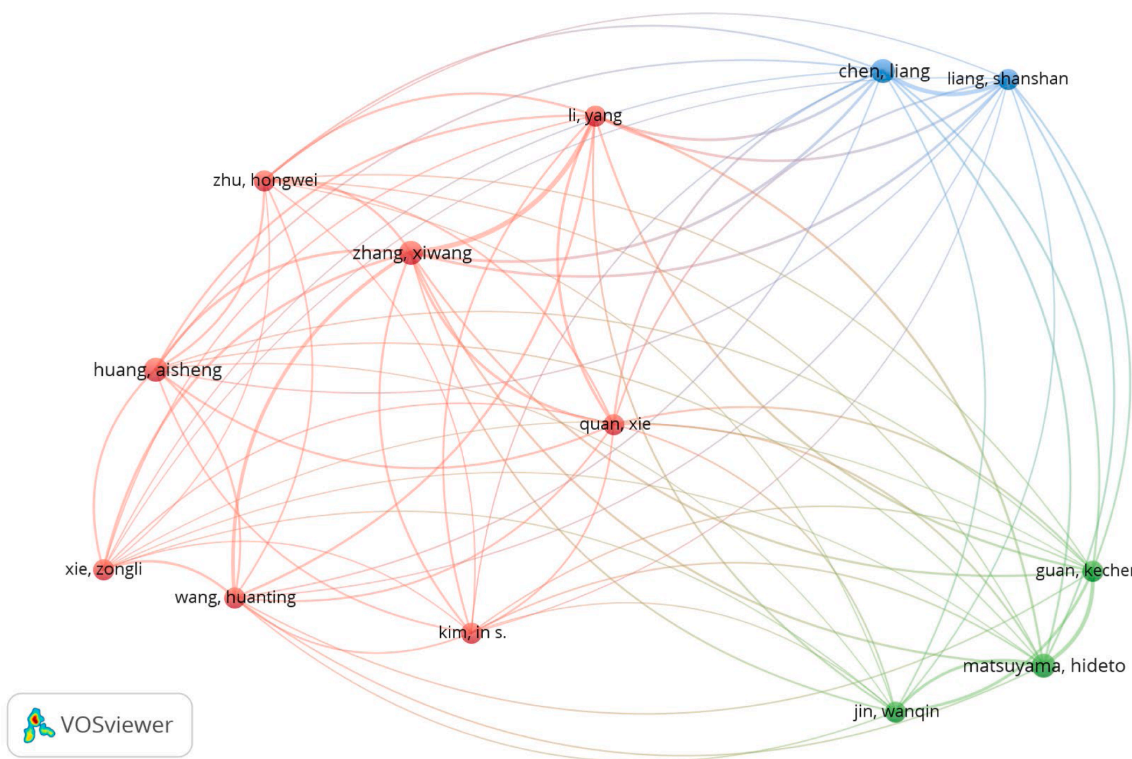

Fig. 7. Bibliographic coupling network visualization (based on unit of analysis authors) on GO-based membranes for desalination applications.

very closely related. Considering the infinitesimal distance between the nodes (articles) and the large number of thicker and thinner lines connecting them, the articles are strongly interlinked in terms of locally citing each other.

Bibliographic coupling based on articles of the unit of analysis has been performed. The resultant network is plotted in Fig. 5. The minimum number of citations for an article is set at 5.

According to the VOSviewer data, 318 articles have been plotted in the network, comprising 8 clusters, 20,219 links, and a total link strength of 49,951. According to the data, the articles exhibit a strong relationship in terms of bibliographic coupling. From the network visualization plot, we can observe that the articles are closely spaced, and the lines connecting them are not visible, indicating a strong correlation between the articles in terms of bibliographic coupling.

Authors

The top-10 authors (in terms of number of publications) and their number of publications, their percentage contribution to the overall number of publications, articles fractionalized (AF), h-index, g-index, m-index, i10 index, TGCS, R index, Q-index, TLCS, and average TLCS per article is summarized in Table 4.

From the table, it can be observed that Huang Aisheng has ranked 1st in terms of number of publications (tie, 6), articles fractionalized (1.95), percentage contribution (%) (tie, 1.57), h-index (tie, 6), g-index (tie, 6), i10-index (tie, 6), R-index (119.5), Q-index (26.78), TGCS (717), TLCS (103), and average TLCS per article (17.17). Considering these factors, Huang Aisheng can be referred to as the most impactful author in our investigation topic. However, considering the m-index (1.25), Chen Liang can be referred to as the most impactful author.

For science mapping, co-authorship network, citation network, bibliographic coupling network, and co-citation network analyses are performed.

Co-authorship network visualization (based on unit of analysis authors) is depicted in Fig. 6. Minimum number of documents of an author and minimum number of citations of an author: both are set to 5 as the

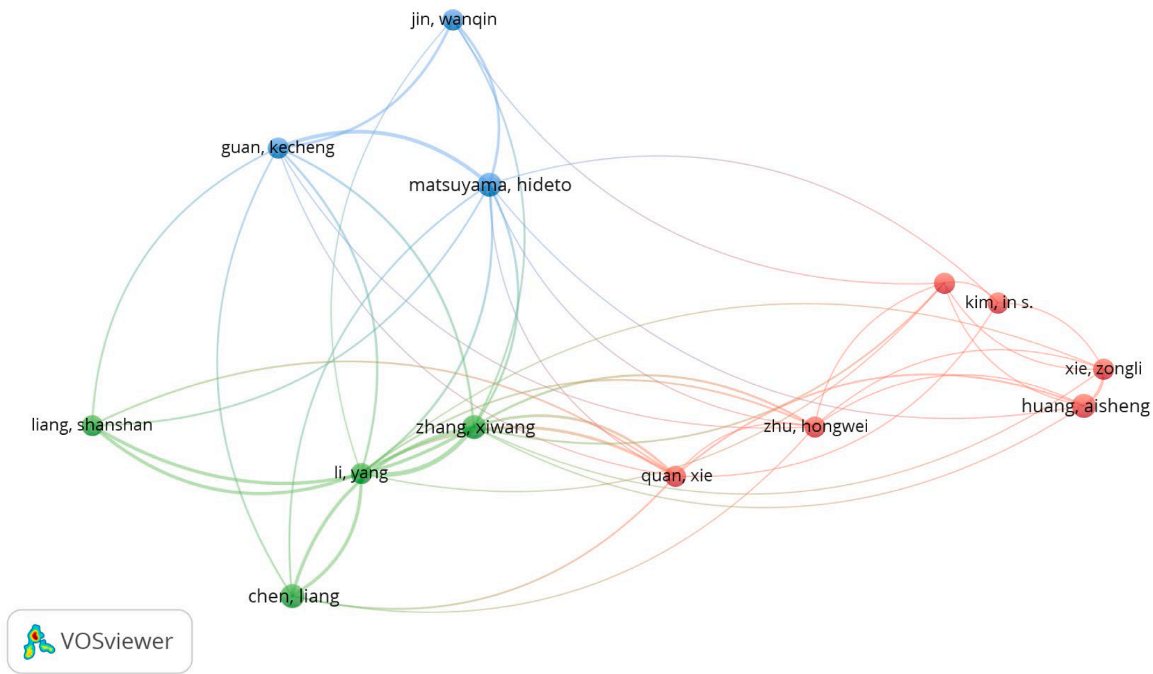

Fig. 8. Citation analysis network visualization (based on unit of analysis authors) on GO-based membranes for desalination applications.

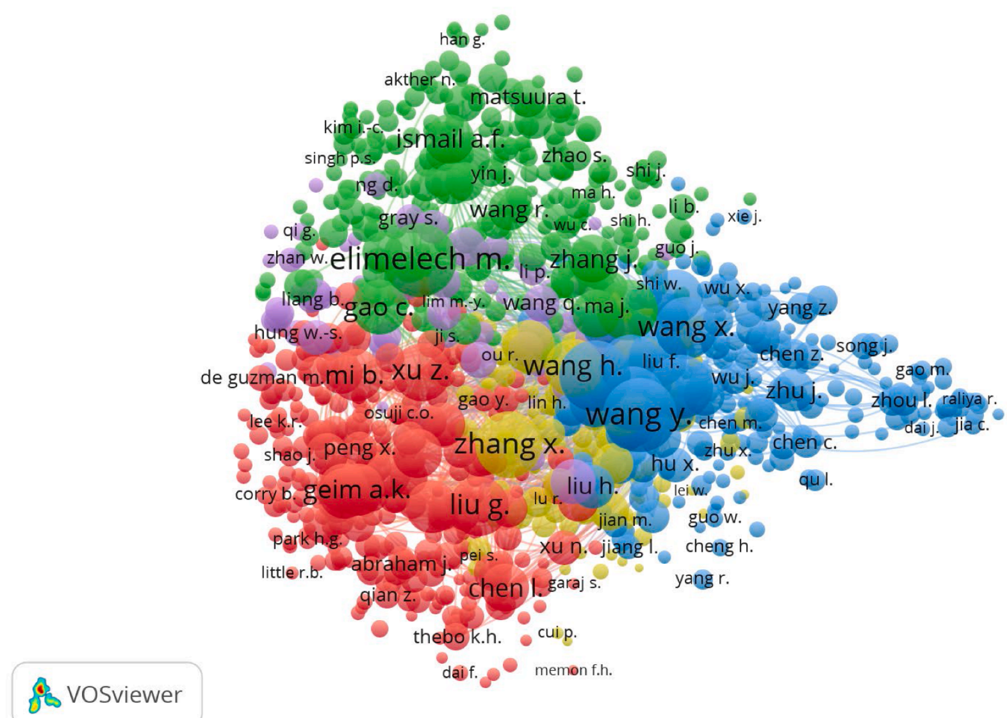

Fig. 9. Co-citation analysis (network visualization) based on unit of analysis authors on GO-based membranes for desalination applications.

threshold.

From the VOSviewer data, there are four items (authors), 2 clusters, four links, and a total link strength of 8. The values clearly indicate a very weak tendency among the authors to become co-authors in articles in our investigated dataset. From the visualization, we can clearly see that there are only four authors, with a few lines connecting them, which indicates a very weak correlation among the authors in terms of co-authorship.

Bibliographic coupling network visualization (based on unit of analysis authors) is depicted in Fig. 7. The minimum number of documents and citations for an author is set at five as the threshold.

According to the VOSviewer data, there are 13 items (authors), 3 clusters, 78 links, and a total link strength of 7634. From the values, it can be clearly observed that the authors have a strong correlation in terms of bibliographic coupling. From the network visualization, we can see that there are a large number of thicker and thinner lines connecting the authors, which is indicative of a strong relationship between authors in terms of bibliographic coupling.

Table 5
Top-10 journals (in terms of number of articles) and their different metrics.

Journal	Number of articles	Percentage contribution (%)	h-index	TGCS	TLCS	Average TLCS per article	CiteScore	Average two year impact factor
Desalination	62	16.23	34	4423	256	4.13	71.339	96.61
Journal of Membrane Science	28	7.33	25	2311	83	2.96	82.536	129.56
Separation and Purification Technology	22	5.76	15	693	1	0.04	31.5	34.24
Journal of Materials Chemistry A	14	3.66	13	1915	117	8.36	136.79	108.8
Membranes	14	3.66	7	150	1	0.07	10.714	17.44
ACS Applied Materials and Interfaces	11	2.88	8	1133	79	7.18	103	164.45
Desalination and Water Treatment	11	2.88	5	144	16	1.45	13.091	23.93
Chemical Engineering Journal	10	2.62	10	458	0	0	45.8	45.8
Carbon	8	2.09	6	374	34	4.25	46.75	58.33
Journal of Environmental Chemical Engineering	7	1.83	6	98	1	0.14	14	18.25

Table 6
The top-10 institutions (in terms of number of articles) and their different metrics.

Institutions	Number of articles	Percentage contribution (%)	TGCS	TLCS	Average TLCS per article
Tiangong University	10	2.62	273	6	0.6
Monash University	9	2.36	650	66	7.333
University of Chinese Academy of Sciences	9	2.36	257	18	2
East China University of Science and Technology	8	2.09	201	1	0.125
Ocean University of China	7	1.83	756	38	5.429
University of New South Wales	7	1.83	445	29	4.143
University of Tehran	6	1.57	431	20	3.333
Beijing University of Chemical Technology	5	1.31	485	44	8.8
Dalian University of Technology	5	1.31	320	19	3.8
Diponegoro University	5	1.31	90	2	0.4

Citation network visualization (based on unit of analysis authors) is depicted in Fig. 8. The minimum number of documents and the minimum number of citations for an author are both set at five as the threshold.

From the VOSviewer data, there are 13 items (authors), 3 clusters, 48 links, and a total link strength of 123 in the network visualization. From the values, there is a moderately good correlation between the authors in terms of locally citing each other's articles. From the network visualization plot, we can observe a moderate number of thicker and thinner lines connecting the items (authors), which is indicative of a moderately good correlation between the authors in terms of locally citing each other's articles.

Co-citation analysis network visualization (based on the unit of analysis: authors) is plotted in Fig. 9. The minimum number of citations for an author is set at 5.

From the VOSviewer data, there are 1000 items (authors), 5 clusters, 425,649 links, and a total link strength of 5023,922. From the values, the authors have a robust correlation in terms of co-citation. From the network visualization plot, we can see that the nodes are very closely spaced, such that the lines connecting them cannot even be seen, which is indicative of strong correlation among the authors in terms of co-citation.

Table 7
The top-10 countries (in terms of number of articles) and their different metrics.

Country	Number of articles	Percentage contribution	TGCS	TLCS	Average TLCS per article
China	165	43.19	7553	386	2.34
Iran	37	9.69	1584	75	2.03
Australia	27	7.07	1551	113	4.185
United States	21	5.5	1944	88	4.19
India	17	4.45	351	7	0.412
South Korea	17	4.45	1608	112	6.59
Egypt	13	3.4	221	5	0.39
United Kingdom	12	3.14	2060	82	6.83
Canada	8	2.09	486	32	4
Japan	7	1.83	399	26	3.71

Journals

The top-10 journals (in terms of number of articles) and their number of articles, impact factor, h-index, TGCS, CiteScore, TLCS, average TLCS per article, and percentage (%) contribution to the overall publishing is summarized in Table 5.

From the table, we can observe that the journal "Desalination" has ranked 1st in terms of number of articles (62), percentage contribution to total publications (16.23), h-index (34), TGCS (4423), and TLCS (256). Considering these metrics, the journal Desalination can be considered to be the most impactful journal in our investigation topic. The "Journal of Materials Chemistry A" has ranked 1st in terms of average TLCS per article (8.36) and CiteScore (136.79), and the journal is the most impactful if these metrics are considered. However, considering the average two-year impact factor (164.45), ACS Applied Materials and Interfaces is considered to be the most impactful journal.

Institutions

The top-10 institutions (in terms of number of articles) and their number of articles, percentage contribution (%) to total publication, TGCS, TLCS, and average TLCS per article is summarized in Table 6.

From the table, it can be observed that Tiangong University has ranked 1st in terms of the number of articles (10) and percentage contribution (%) to total publications (2.62), which indicates that researchers from this university are working the most on our investigated topic. If we consider TGCS (756), the Ocean University of China has ranked 1st, while Monash University has ranked 1st in terms of TLCS (66), and the Beijing University of Chemical Technology has ranked 1st in terms of average TLCS per article (8.8).

Countries

The top-10 countries (in terms of number of articles) and their

Table 8
The top-20 burst keywords, their burst period, burst strength, and their recent frequency.

Burst keyword (trigram)	Start	End	Strength	Recent frequency
Graphene oxide membrane	2015	2024	3.59	162
Graphene/graphite oxide	2018	2023	6.83	17
Photothermal membrane distillation	2019	2020	6.64	16
Forward osmosis system	2017	2024	5.8	34
Sodium chloride rejection	2017	2024	4.82	55
Water flux performance	2015	2023	3.9	78
Reverse osmosis membrane	2018	2021	4.86	38
Desalination forward osmosis	2017	2024	5.69	16
Functionalized graphene oxide	2017	2023	5.8	10
Water filtration efficiency	2016	2024	4.44	43
Graphene oxide show	2017	2022	5.69	9
Graphene oxide composite	2017	2024	4.92	26
Flux low water	2017	2023	5.55	9
Salt rejection rate	2015	2022	3.19	68
Mixed matrix membrane	2017	2023	5.55	6
Graphene oxide reduce	2015	2024	3.83	48
Water purification desalination	2018	2024	3.32	48
Ion selectivity mechanism	2016	2024	4.44	19
Graphene modification oxide	2022	2024	4.72	9
Filtration treatment water	2020	2024	4.13	24

number of articles, percentage contribution (%) to the total number of articles, TGCS, TLCS, and average TLCS per article is summarized in Table 7.

From the table, it can be observed that China has ranked 1st in terms of the number of articles (165), percentage contribution (%) to total publications (43.19), TGCS (7553), and TLCS (386). Considering these metrics, China is the most impactful in our investigation topic. However, considering the average TLCS per article (6.83), the United Kingdom is the most impactful country in our topic investigation.

Burst keywords analysis

The top-20 burst keywords, determined using Kleinberg's burst detection algorithm, have been identified to pinpoint research hotspots. The burst keywords are selected as trigrams, because bigrams and monograms often do not render meaningful interpretation. The burst keywords (trigrams), their burst period, burst strength, and their recent frequency (2019–2024) are summarized in Table 8.

For better visualization, the top-20 burst keywords are plotted in Fig. 10.

The burst period of the trigram "water flux performance" ended in 2023, with a recent frequency of 78. Research into graphene oxide (GO)-based membrane water flux performance for desalination applications is expected to expand due to multiple strong motivating factors. GO-based membranes achieve superior water flux and salt rejection performance through their distinctive water channels and adjustable functional properties [51–53]. The adjustable interlayer distance and surface characteristics of GO membranes enable researchers to enhance both water permeability and selectivity, which are essential for effective desalination processes [54,55]. The implementation of cross-linking agents and nanoparticle integration during fabrication produces GO membranes with enhanced stability and reduced fouling properties, which extend their practical application duration [56]. Theoretical investigations, together with experimental results, show that GO membranes outperform traditional polymeric membranes by delivering high water flux rates and superior salt rejection performance [57,58]. The development of hybrid GO membranes alongside new materials and

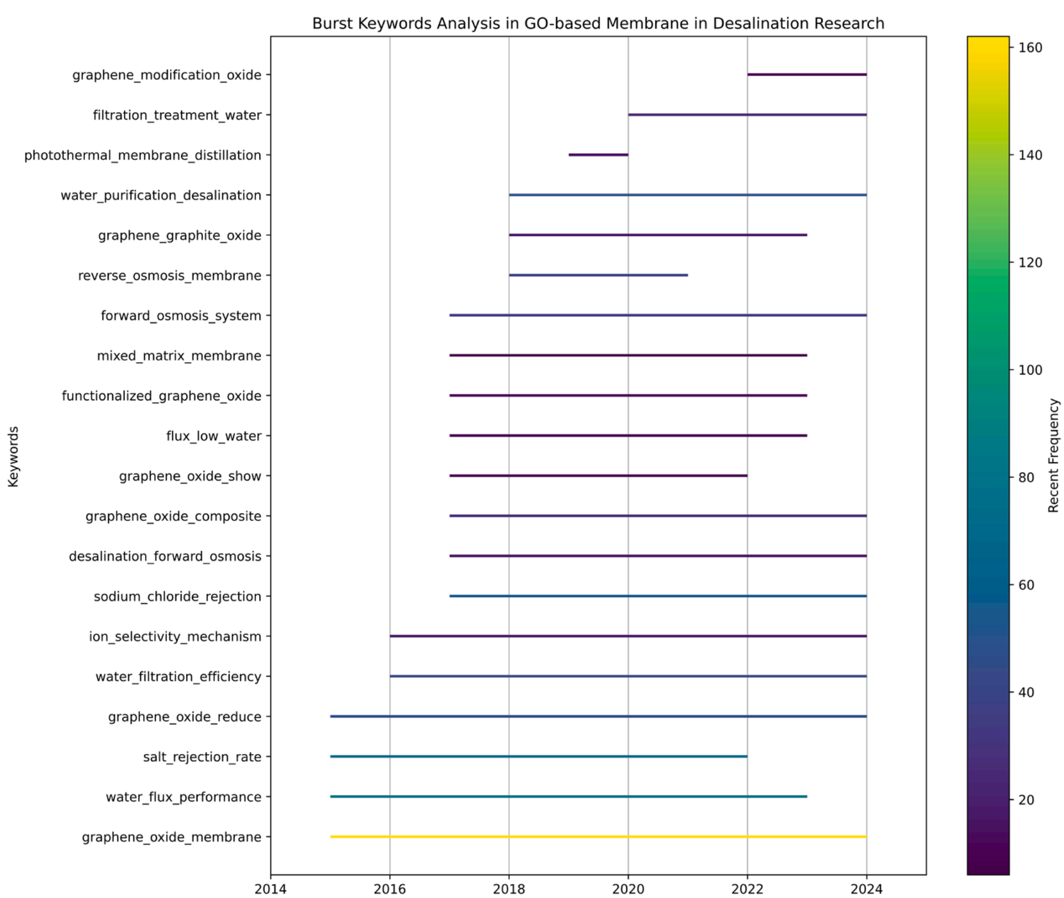

Fig. 10. Top-20 burst keywords on GO-based membranes for desalination applications.

electric-driven enhancement methods and pressure-assisted filtration techniques expands the desalination capabilities of GO-based membranes [59,60]. The combination of technological progress with the rising worldwide need for efficient, sustainable water treatment systems drives scientists to focus on improving the water flux performance of GO-based membranes.

The burst period of the trigram "salt rejection rate" ended in 2022 with a recent frequency of 68. Research on graphene oxide (GO)-based membrane salt rejection rates for desalination applications will experience stability or decrease because of multiple built-in obstacles that affect these materials. The primary issue with GO membranes stems from their permeability-selectivity trade-off, as achieving high salt rejection necessitates extremely low water permeance rates that fail to meet practical requirements [61]. The drying techniques used for GO membrane preparation have two main effects on their structural properties, as they control both hydrophilic characteristics and nanochannel dimensions, which determine water flow rates and salt barrier efficiency [62]. The expansion of the GO membrane interlayer distance following ion absorption results in larger nanochannels but simultaneously reduces water permeance, creating challenges for achieving both high salt rejection and water flux performance [63]. The creation of in-plane nanopores and GO functionalization with other materials for water flux improvement results in decreased salt rejection performance or necessitates complicated modifications that prove challenging to scale up and maintain economic feasibility [64]. GO-based membranes show potential for desalination, but research on salt rejection rates remains stagnant because scientists continue to face difficulties in resolving fundamental limitations to achieve suitable water flux and salt rejection performance.

The burst period of the trigram "sodium chloride rejection" ended in 2024, with a recent frequency of 55.Research on sodium chloride (NaCl) rejection in graphene oxide (GO)-based membranes for desalination applications is expected to expand due to several key factors. GO membranes possess physical and chemical properties that make them suitable for water purification and desalination operations [65,66]. The operation of GO membranes faces difficulties because their high salt rejection performance results in decreased water permeance [67]. The incorporation of carbon nanotubes (CNTs) and polyvinyl alcohol (PVA) into recent developments has proven effective in improving both permeability and selectivity [68]. Research indicates that external pressure regulation (EPR) and electrokinetic effects improve both NaCl rejection and water flux performance [69]. The research team conducts molecular dynamics simulations to optimize pore dimensions and interlayer distances, which leads to better salt rejection and water permeability [70,71]. The GO membrane stability and performance are enhanced through two modification methods, which are cation intercalation and nanopore creation [72,73]. The analysis of the articles depicts the reason why sodium chloride rejection in GO-based membranes for desalination is a research hotspot.

The burst period of the trigram "forward osmosis system" ended in 2024 with a recent frequency of 34. The research on forward osmosis (FO) systems will focus on graphene oxide (GO)-based membranes for desalination because of several key factors. The water flux and salt rejection performance of GO-based membranes exceed those of traditional polymeric membranes, making them suitable for desalination operations [74]. The incorporation of GO into FO membranes results in better hydrophilic characteristics and enhanced porosity and structural stability, which are necessary for achieving high-performance desalination [75]. Researchers use GO membrane engineering to develop thin structures with tunable pore dimensions, which produce fast water transport and low salt leakage [76]. The stability and water absorption properties improve through chemical modifications that include reduction and polydopamine coating for hydrophilic layers, which solve the stability and hydrophobicity problems in reduced GO laminates [77]. The GO-based membranes have demonstrated successful operation in real seawater environments, achieving both high water permeation rates and effective salt removal capabilities, which are vital for desalination systems [78]. The development of GO membrane fabrication and modification methods, utilizing different GO flake sizes and polymer coatings, drives FO desalination technology advancement into future research directions.

The burst period of the trigram "ion selectivity mechanism" ended in

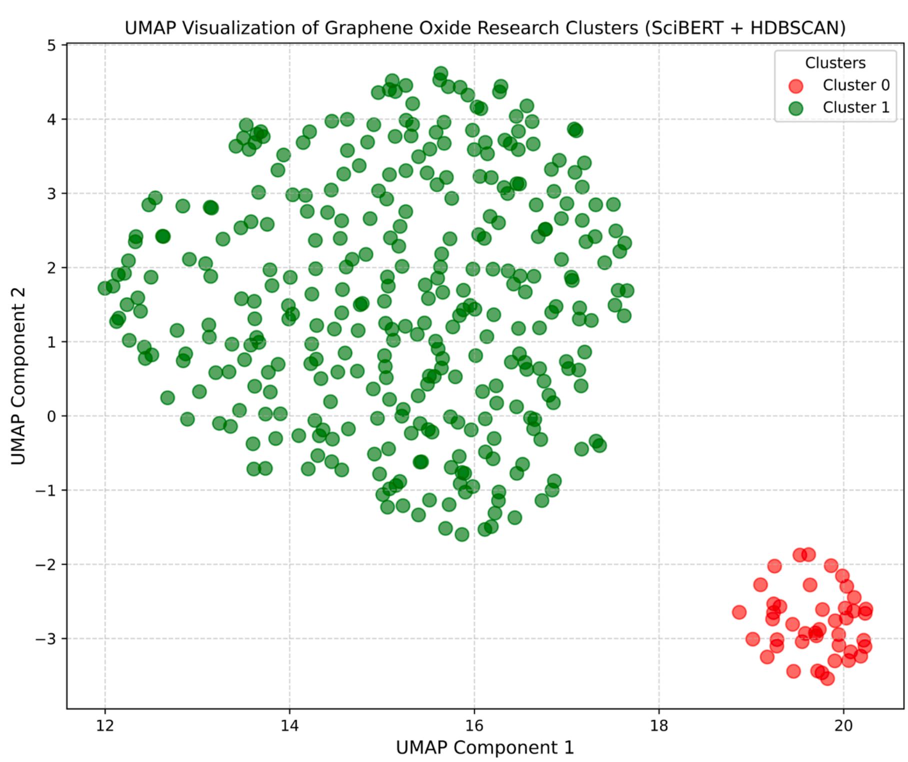

Fig. 11. Topic modeling using SciBERT, HDBSCAN, and UMAP.

Table 9
Key findings of representative documents of cluster 0 and their references.

Key findings	References
This article details the fabrication of cost-effective, biopolymer-based photothermal membranes for seawater desalination using a direct solar steam generation (DSSG) strategy. The research determined that a freeze-dried membrane composed of sodium alginate (SA) and polyvinyl alcohol (PVA) in a 3:1 ratio yielded the best results. Enhanced with graphene oxide as a photothermal absorber, this optimal membrane achieved a high water evaporation rate of 4.33 $kg/m^2/h$ under 1-sun illumination.	[94]
The research investigates two methods to enhance commercial reverse osmosis (RO) membrane performance through PAA grafting and GO nanosheet surface integration. The research identified 1.5 mM PAA and 0.1 wt % GO modification of the membrane as the combination that produced the most effective results. This modified membrane achieved the highest water flux among the modified membranes (37.1 L/m^2h), 98 % NaCl rejection, and superior antifouling efficiency	[95]
The research describes a method to create inexpensive forward osmosis membranes through the combination of cellulose triacetate (CTA) with graphene oxide (GO), which originates from palm fronds waste. The polyamide thin-film composite (TFC) membrane with a 0.3 % GO content on CTA support achieved the best results, reaching a water flux of 35 L/m^2h and a reverse salt flux of 1.1 g/m^2h. The optimized TFC membrane achieved superior desalination results during testing with actual Red Sea seawater, which demonstrates its suitability for industrial water desalination operations.	[96]
This article details the fabrication of polysulfone (PSf) mixed-matrix membranes enhanced with amine-functionalized graphene oxide ($GO—NH_2$) for water treatment and air dehumidification. The research showed that the 0.2 wt. % $GO—NH_2$ membrane achieved the highest performance results by increasing water permeability by 92 % and oil rejection by 95.6 % while maintaining 88 % flux recovery. The optimal membrane achieved better air dehumidification performance due to its 20 % higher water vapor permeance compared to a pure PSf membrane.	[97]
This article details the fabrication of novel thin-film nanocomposite (TFN) reverse osmosis membranes by embedding β-cyclodextrin functionalized graphene oxide (β-CD-f-GO) into a polyamide layer. The membranes showed a 38 % improvement in water permeation flux while preserving their salt rejection performance at the original level. The β-CD-f-GO membranes showed better antifouling properties and increased antibacterial activity by 45.9 % and better chlorine resistance than standard membranes.	[98]
This article details the fabrication of mixed matrix membranes by blending reduced graphene oxide (rGO) into a polyvinylidene fluoride (PVDF) polymer solution for desalination via membrane distillation. The research showed that a membrane containing 1.36 wt % rGO delivered the best results by producing a permeate flux of 34.69 $L/m^2/h$. All fabricated membranes exhibited excellent salt rejection of 99.99 % and proved stable over a 40-hour desalination process.	[99]
This article describes the fabrication of novel outer-selective hollow fiber (OSHF) membranes for forward osmosis (FO) applications by incorporating size-controlled graphene oxide (SGO) nanosheets into a polyamide (PA) layer. The membrane with a 0.0005 wt % SGO content delivered the highest performance, achieving a water flux of 39.0 $L\ m^{-2}h^{-1}$ and a specific reverse solute flux of 0.16 $g\ L^{-1}$. Standard membranes failed to match the performance of SGO-based membranes because these membranes demonstrated enhanced fouling resistance and superior cleaning efficiency.	[100]
This article details the fabrication of polyvinylidene fluoride (PVDF) reverse osmosis membranes enhanced with graphene oxide (GO) and zeolite (Zeo) nanofillers for desalination. The research showed that GO- and zeolite-treated membranes achieved the best performance because they enabled water to flow at 34.5 L/m^2h while blocking salt with 100 % efficiency. The results show better performance than standard PVDF membranes because they achieved a water flux of 15.6 L/m^2h and 82.8 % salt rejection.	[101]
This article details the fabrication of novel composite nanofiltration membranes by incorporating polyphenol-etched hollow metal-organic frameworks (eZIF-8) into graphene oxide (GO) nanosheets. The membrane with a 62.5 wt % eZIF-8 content delivered the best results, with a permeate flux of 16.4 $L\ m^{-2}\ h^{-1}\ bar^{-1}$, which exceeded that of pure GO membranes by 382 %, while maintaining 86.3 % salt rejection. The composite membranes demonstrated superior stability and better fouling resistance, making them suitable for desalination and water treatment operations.	[102]
This article details a novel approach to enhance the stability of graphene oxide (GO) membranes for produced water treatment by combining low-temperature thermal reduction and metal cation (Zn^{2+} and Fe^{3+}) crosslinking. The Zn^{2+}-crosslinked GO membrane achieved the highest water flux of 8.3 $L\ m^{-2}\ h^{-1}$ after thermal reduction (Zn^{2+}–rGO), but Fe^{3+} –rGO demonstrated superior mechanical properties and organic compound rejection at 69 %. The modified membranes demonstrated salt rejection performance exceeding 99 % which proved that pervaporation technology works well for treating water solutions containing high salt concentrations.	[103]

2024 with a recent frequency of 19. The study of ion selectivity mechanisms in graphene oxide (GO)-based membranes for desalination applications is expected to grow due to multiple strong motivations. The high water permeability and ion rejection rates of GO membranes make them suitable for efficient desalination applications [79]. The precise molecular sieving properties of GO membranes result from their unique 2D interlayer nanostructure, which allows fast water movement while blocking ions. The current understanding of water and ion transport through nanochannels requires further investigation, as it remains incomplete. GO membranes experience two main obstacles because their selectivity and permeability performance are restricted by a trade-off relationship [80]. Scientists can develop optimized membrane structures that achieve maximum selectivity and permeability through their research on ion selectivity mechanisms based on detailed studies [80]. The addition of potassium ions to GO membranes results in improved ion rejection performance, indicating that researchers can modify ion selectivity by adding specific ions [81,82]. The creation of GO membranes with nanochannel chemistry based on biological ion channels shows potential for constructing highly efficient ion-selective systems [83]. The development of ion selectivity mechanisms in GO-based membranes requires further research to achieve better desalination technology performance.

The burst period of the trigram “water filtration efficiency” ended in 2024 with a recent frequency of 43. The research on GO-based membrane desalination efficiency is expected to advance due to several influential motivating factors. The GO membranes possess distinctive characteristics, including high water permeability and adjustable interlayer spacing, making them suitable for desalination applications [84–86]. The membranes can be engineered to improve water flux and maintain high salt rejection rates, which solves the traditional problem of permeability versus selectivity [87,88]. The addition of functional groups and cross-linking agents to GO membranes enhances their structural stability and separation performance, which enables their use in demanding applications for extended periods [89,90]. GO membrane functionalization with carminic acid and other natural compounds results in improved water permeability and contaminant removal capabilities [91]. The integration of GO with bismuth oxybromide in composite membranes leads to improved photocatalytic self-cleaning capabilities, which decrease fouling and increases membrane durability [92]. The ability to fine-tune the nanochannel dimensions and the interlayer spacing of GO membranes enables precise control over the filtration process, making them highly adaptable to various desalination needs [93]. Scientists study GO-based membranes for desalination because emerging technologies match the expanding need for efficient, sustainable water purification systems in the market.

Artificial intelligence (AI)-models derived analysis

Topic modeling using SciBERT, HDBSCAN, and UMAP

To uncover the latent topics within the dataset, topic modeling has been performed using SciBERT, HDBSCAN, and UMAP. SciBERT performs the function of natural language processing (NLP), while

Table 10
Key findings of representative documents of cluster 1.

Key findings	References
The authors present a new method to boost both water permeability and ion separation performance in GO/CNT membranes through external voltage application. The researchers demonstrated that applying 3.0 V across the non-conductive separation layer increased water flux to 17.4 L m^{-2} h^{-1} while achieving 78.3 % NaCl rejection from 52.4 %—the dual improvement results from electrokinetic water transport mechanisms and better ion distribution patterns.	[69]
This article describes the fabrication of a low-cost, 3D photoevaporation membrane for desalination, utilizing an environmentally friendly geopolymer support and a reduced graphene oxide (rGO) photothermal layer. The 3D pyramid-shaped membrane (3D-G/rGO) reached an evaporation rate of 2.39 kg/m^2/h under 1-sun solar intensity. The study also found its performance could be dramatically enhanced to 91.2 kg/m^2/h using low-temperature waste heat, demonstrating strong potential for industrial wastewater treatment.	[104]
This article details the fabrication of a stable graphene oxide (GO)-based pervaporation membrane by cross-linking GO with sulfonate-containing diamine molecules (DBS) and applying a protective coating of polyvinyl alcohol (PVA) and chitosan. The optimized membrane (PCGO+DBS/PP) achieved the best results, showing 99.99 % salt rejection throughout the entire test period, even under the most demanding temperature fluctuations. The composite membrane exhibited excellent anti-fouling properties, minimal flux decline, and good reusability after chemical cleaning.	[105]
This article details the fabrication of Janus hollow fiber membranes by anchoring a hydrophilic graphene oxide (GO)/poly(vinyl alcohol) (PVA) layer onto a hydrophobic polypropylene (PP) support for membrane distillation. The membrane showed better water resistance and surface protection while maintaining water permeability at 4.6 kg/m^2h and achieving salt rejection rates above 99.9 % when treating real seawater and industrial leachate at 80 % water recovery. This stable performance is attributed to the novel intrusion-anchored structure of the hydrophilic layer.	[106]
This article details the fabrication of a robust, anti-wetting composite membrane by spray-coating a reduced graphene oxide (rGO) layer onto a polytetrafluoroethylene (PTFE) substrate. The optimized rGO-PTFE membrane achieved superior performance and durability because it maintained salt rejection above 99.9 % while achieving water flux levels of 60 L·$m^{-2}$$h^{-1}$ during a 66-hour test using surfactant solutions. The membrane system achieved a remarkable water flux of 149 L/m^2/h when operating at high temperature differences, surpassing the water flux of every existing membrane system.	[107]
This article details the first-ever fabrication of novel graphene oxide/polyimide (GO/PI) hollow fiber membranes for seawater desalination using a direct spinning method. The membranes showed excellent performance because they reached a water flux of 15.6 kg m^{-2} h^{-1} while maintaining 99.8 % salt rejection at 90 °C. The GO/PI membranes demonstrated stable operation during a 120-hour desalination test, confirming their stabilization.	[108]
This article details the fabrication of a robust graphene oxide (GO) membrane for desalination, created by cross-linking GO with thiourea (TU) and then treating it with potassium hydroxide (KOH). The TU-GO-KOH membrane achieved superior performance after fabrication because it achieved water permeance of ~14.2 L m^{-2} h^{-1} and NaCl rejection of ~86.3 %. The membrane maintained its structural integrity and mechanical and chemical properties during exposure to severe conditions, which included high pressure, ultrasonication, and extreme pH values.	[109]
The authors describe their method for creating a new polymer-intercalated graphene oxide (GO) membrane which solves the major swelling problems that traditional GO membranes experience during membrane distillation. The membrane showed outstanding performance because it reached 52 L $m^{-2}$$h^{-1}$ water flux while completely blocking small ions and retaining 98 % of volatile phenol. The nanochannel structure operates as an exact molecular sieve because it maintains stable narrow channels that function as precise molecular sieves.	[110]
This article details a novel "confined interfacial polymerization" strategy to fabricate an ultrathin polyamide-graphene oxide (PA-GO) composite membrane for desalination. The membrane achieved outstanding results, reaching 99.7 % NaCl rejection and a water permeance of 3.0 L m^{-2} h^{-1} bar^{-1}. The PA-GO membrane outperformed standard polyamide membranes through its superior long-term stability, antifouling properties, and chlorine resistance.	[111]
This article details the fabrication of a novel bi-photothermal membrane for solar-driven desalination by combining silver-loaded graphene oxide (GO-Ag) with a polyacrylonitrile (PAN) nanofiber network. The GO-Ag/PAN membrane optimized for performance reached a water evaporation rate of 1.61 kg $m^{-2}$$h^{-1}$ while maintaining salt rejection above 99.9 % under 1-sun illumination. The membrane achieves high efficiency because it absorbs 97 % of the light and converts 93.3 % of the absorbed light into heat.	[112]

HDBSCAN performs the function of clustering, and UMAP performs the function of dimensionality reduction and visualization. The result is visualized in Fig. 11.

An average silhouette score of 0.594 has been observed, indicating that the clusters are moderately aggregated. A Davies-Bouldin Index value of 0.3983 indicates that the clusters are distinctively separate.

Key findings of the representative document of cluster 0 and cluster 1 are summarized in Table 9 **and** Table 10**,** which will help to assign a topic name to each of the clusters.

Key findings of representative documents of cluster 0

Based on the key findings, cluster 0 can be named as "Graphene Oxide-Enhanced Nanocomposite Membranes for Desalination."

Key findings of representative documents of cluster 1

Based on the key findings, cluster 1 can be named as "Cross-Linked and Layered Graphene Oxide Membranes for Advanced Desalination."

Research evolution forecast using Prophet

To predict the future research on the modelled topics in the previous section, a research evolution forecast is performed. The result is plotted in Fig. 12**.**

The R^2 value for the topic "Graphene Oxide-Enhanced Nanocomposite Membranes for Desalination**"** is 0.4799 due to a low number of input data (articles and publication year), and the R^2 value for the topic "Cross-Linked and Layered Graphene Oxide Membranes for Advanced Desalination" is 0.9277, indicating that it can accurately predict the research evolution forecast.

The forecasted number of publications on the modelled topic is summarized in Table 11**.**

Research on graphene oxide (GO)-enhanced nanocomposite membranes for desalination is expected to slow down due to several challenges, including the instability and low flux of these membranes in industrial applications, as well as the distortion of nanochannels caused by the hydration of oxidized groups, which compromises selectivity and water transport dynamics [113–115]. The production of thin-film nanocomposite (TFN) membranes with GO has shown better performance, but the complicated nature of oversized production methods blocks their market availability [116]. The research on cross-linked and layered GO membranes will grow because these materials show better stability, perm-selectivity, and structural integrity. Cross-linking with various agents, such as borate, poly(vinyl alcohol), and amino acids, has been demonstrated to enhance the stability and performance of GO membranes by creating a more robust and selective three-dimensional framework [117–119]. The new developments tackle membrane swelling and structural breakdown problems, which enhance the potential of cross-linked and layered GO membranes for future desalination operations.

Technological advancement on GO-based membranes for desalination

Patents publication over time

An overview of patent publications over time on our investigated topic is plotted in Fig. 13**.**

As we can observe, compared to the almost steadily increasing research publications, there is an irregular trend in the case of patent

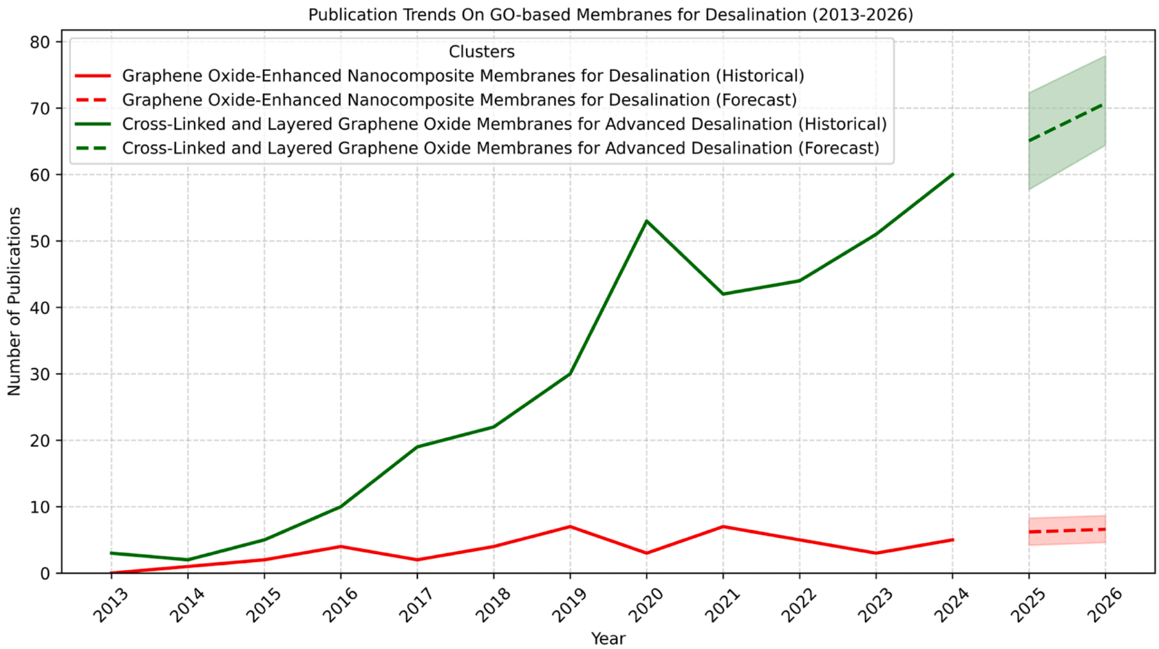

Fig. 12. Research evolution forecast using SciBERT, HDBSCAN, and Prophet.

Table 11
Forecasted number of publication on both the modelled topics with the publication range at 95 % confidence intervals (CI).

Topic	Year	Forecasted publications	95 % CI (Confidence Interval)
Graphene Oxide-Enhanced Nanocomposite Membranes for Desalination	2025	6	4–8
	2026	7	5–9
Cross-Linked and Layered Graphene Oxide Membranes for Advanced Desalination	2025	64	58–71
	2026	70	62–77

publications on GO-based membranes for desalination. The irregular trend in patent publication for graphene oxide (GO)-based membranes in desalination applications can be attributed to several factors. The field continues to develop as scientists conduct ongoing studies to address essential problems that affect GO membrane stability, permeability, selectivity, and large-scale production capabilities [120]. The process of GO nanoplate oxidation creates structural changes in nanochannels, which disrupt water transport properties and selectivity, so researchers must develop new membrane designs and functionalization methods [121]. The wide range of research topics, experimental methods, and applications being studied by authors through their publication keywords leads to variable patent activity levels [122]. The process of moving laboratory-based research to commercial viability faces multiple technical and economic challenges, which demand precise transport pathway development and stable performance in industrial settings [123]. The ongoing difficulties with GO-based membrane development and the requirement for new multifunctional nanocomposite materials and large-scale manufacturing techniques result in inconsistent patent publication patterns because scientists work to create functional and efficient GO-based desalination membranes.

Top applicant list

The top applicant list of the patent application for GO-based membrane for desalination application is plotted in Fig. 14.

The Nitto Denko CORP has ranked 1st among the top applicants (20) by a large margin. However, as we can note from the top applicant list, the University of Manchester (7), Massachusetts Institute of Technology (6), King Fahad University of Petroleum and Minerals (6), Nanjing University of Technology (5), and Ngee Ann Polytechnic (5) have contributed to the patent application on GO-based membranes for desalination applications. None of the institutions ranked among the top 10 in the bibliometric analysis in the dataset from the Scopus database. Thus, the institutions are more centered on real-life technological development rather than laboratory-scale research.

Patents by jurisdiction

Patents on GO-based membranes for desalination by jurisdiction are plotted in Fig. 15.

As we can observe, the United States has 109 patents, while China has 104 patents, differing by a narrow margin. However, the United States ranked 4th in terms of bibliometric analysis performed in the dataset from the Scopus database, which indicates the United States is maintaining both laboratory research and technological development on GO-based membranes for desalination applications. Australia has 3 patents and also ranked 3rd in bibliometric analysis from the Scopus database, and thus it can be said that the country maintains both laboratory research and scale up innovations. Mexico (1), and Singapore (1) have patents on GO-based membranes for desalination applications, while they are not listed in the top 10 countries in the bibliometric analysis section. Thus, countries are more inclined to scale up technological development rather than focusing on laboratory research.

Top owner list

The top owners of the patents on GO-based membrane for desalination application are plotted in Fig. 16.

As we can observe from the figure, Ide Water Technologies LTD and Membrane Recovery LTD have ranked first jointly with eight patents on our investigation topic. However, Nitto-Denko Corporation and Lockheed Martin Corporation have jointly ranked second, with six patents each on our investigation topic. Nitto-Denko Corporation has applied for 20 patents, and as of the day of investigation, 6 of them have been approved.

Top inventors list

The top inventors (in terms of number of patents) on GO-based

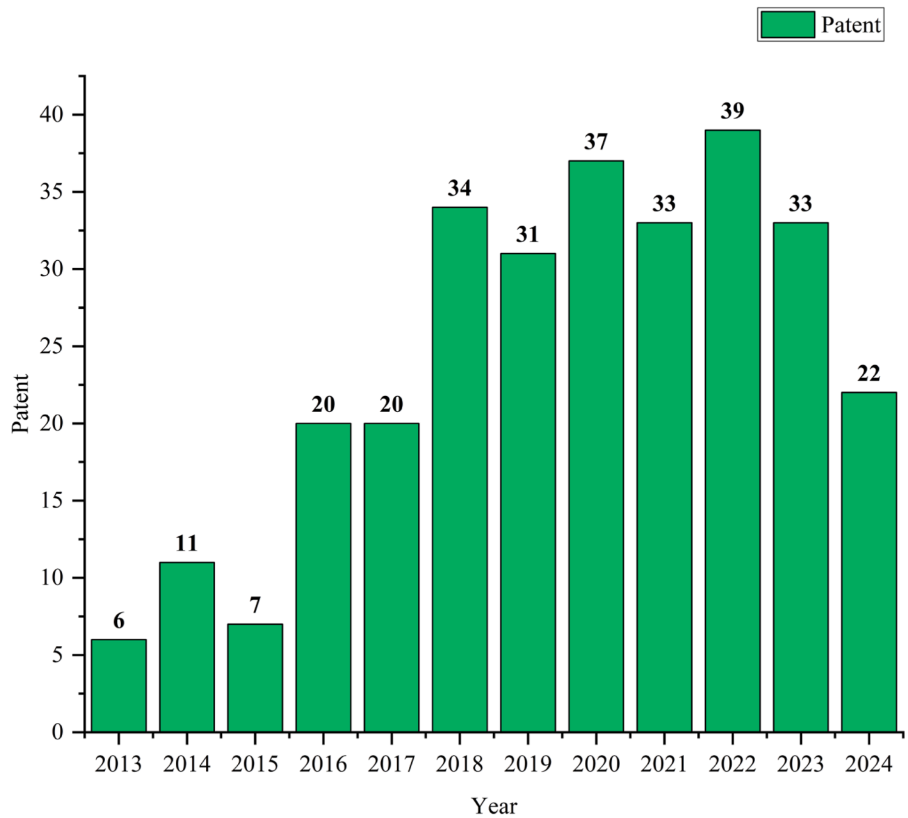

Fig. 13. No. of patent publication over time on GO-based membranes for desalination.

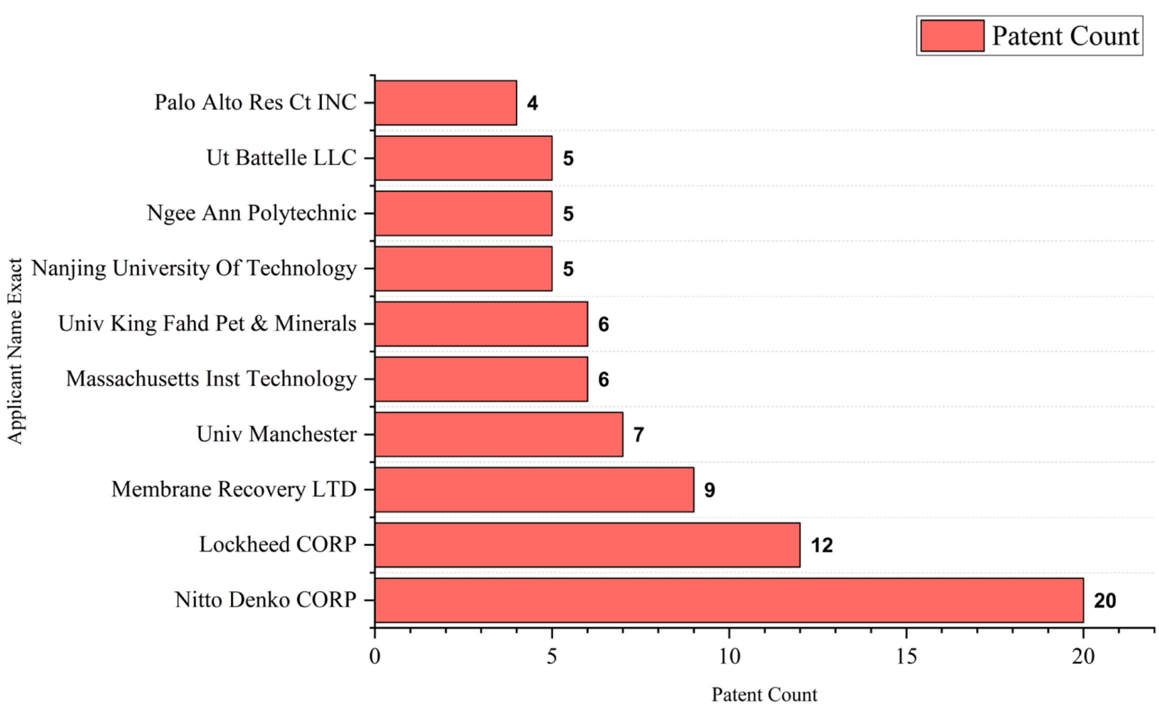

Fig. 14. Top applicant list for patent application on GO-based membranes for desalination application.

membranes for desalination applications are plotted in Fig. 17.

As we can observe from the figure, scientists Kitahara Isamu, Lin Weiping, Wang Peng, and Yamashiro Yuji have jointly ranked first with 19 patents on our investigation topic. We can observe that no authors from this analysis were listed in the top-10 authors' bibliometric section. Thus, while experimental researchers provide key findings on a topic, the scientists behind the patents are more inclined to scale up research from laboratory to industrial scale to bring technological developments.

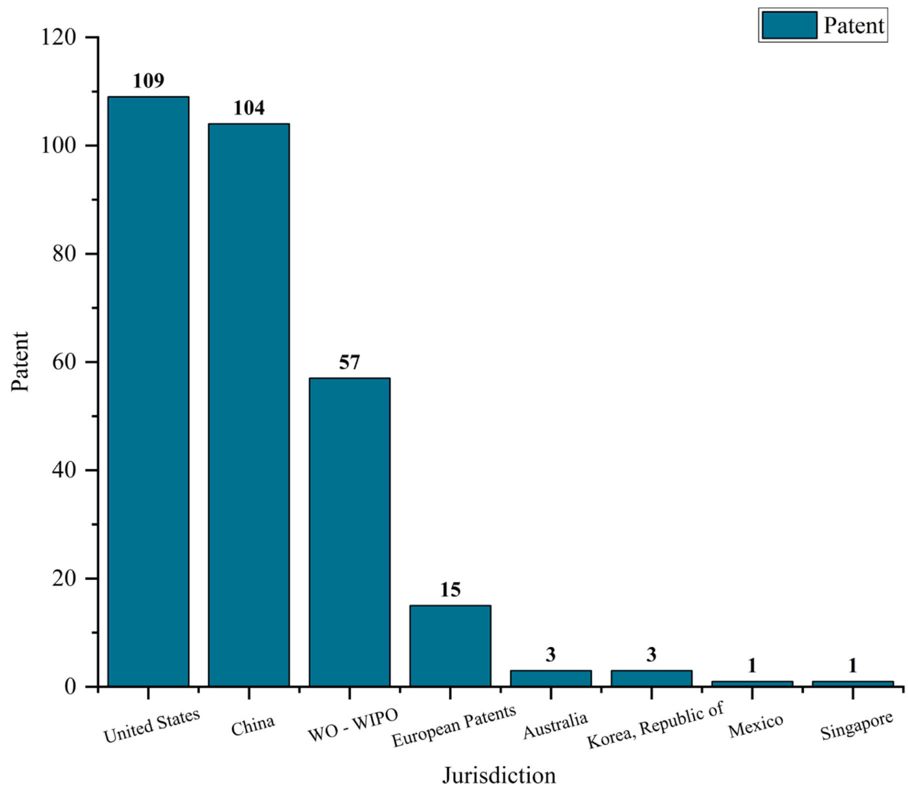

Fig. 15. Patent by jurisdiction on GO-based membranes for desalination applications.

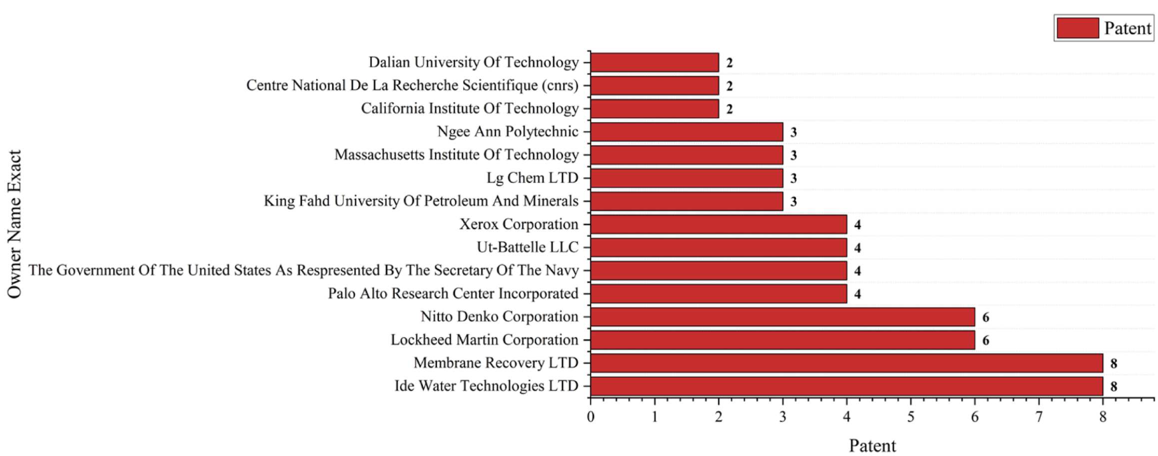

Fig. 16. Top owners of patent on GO-based membrane for desalination applications.

Top cited patents

The top-10 patents, along with their titles, application numbers, and citation counts, are summarized in Table 12.

The top 10 patents, listed by patent count, title, and application number, are provided in Table 13.

Industrialization challenges of GO-based membranes for desalination applications

Graphene oxide (GO)-based membranes exhibit great potential for desalination due to their high water permeability, mechanical strength, and selectivity; however, multiple industrialization obstacles hinder their widespread use at scale [124,125]. Key obstacles include difficulties in fabricating continuous, defect-free GO-nanosheets at large scale, which is essential for industrial use but remains economically unviable with current methods [124,125]. The membrane structures of graphene oxide (GO) face challenges in achieving stability and scalability because GO-based membrane swells and delaminates in water, resulting in decreased mechanical stability and reduced salt rejection performance over time [126–128]. The current inability to precisely control interlayer spacing and prevent swelling hinders both the operational stability and separation performance of the system [129–131]. Additionally, balancing high water flux with effective salt ion removal remains a technical challenge, as improvements in one often come at the expense of the other [132,133]. The technology faces operational challenges for commercial use due to high pressure, which causes membrane disintegration, low ion rejection, and potential biofouling problems [134,135]. Environmental concerns also arise from the non-eco-friendly reduction treatments often used in GO membrane fabrication, which can hinder sustainable industrial practices [125]. The

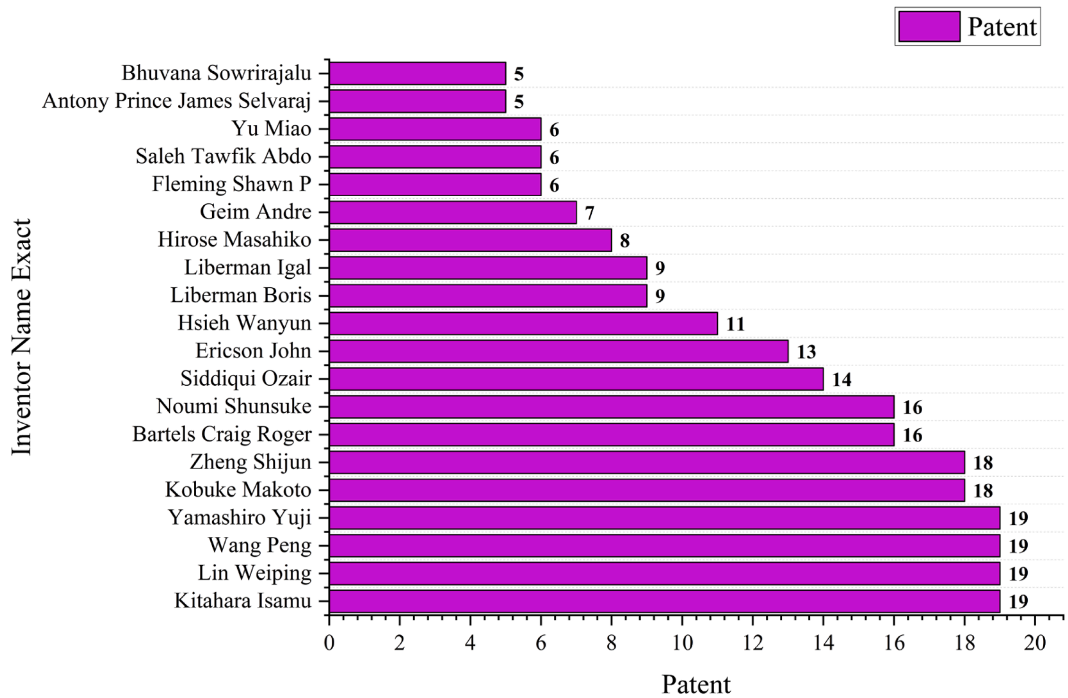

Fig. 17. Top inventors list (in terms of number of patents) on GO-based membranes for desalination applications.

Table 12
Top-10 patents (in terms of cites patent count) and their title, application number, and cites patent count.

Title	Application number	Cites Patent Count
Thermal interface material (TIM) with thermally conductive integrated release layer	US 201,715,484,391 A	107
Thermal interface material (TIM) with thermally conductive integrated release layer	US 201,213,495,132 A	96
High-flux thin-film nanocomposite reverse osmosis membrane for desalination	US 201,816,485,510 A	74
Lightweight inorganic membrane module	US 201,916,701,279 A	53
Nanoporous membranes and methods for making the same	US 201,414,200,530 A	49
Superhydrophobic coated micro-porous carbon foam membrane and method for solar-thermal driven desalination	US 201,916,583,593 A	39
Methods for chemical reaction perforation of atomically thin materials	US 201,414,200,195 A	37
Multilayer thin film nanocomposite membranes prepared by molecular layer-by-layer assembly	US 201,616,329,653 A	28
Graphene oxide modified separation membrane based on electrostatic spraying as well as preparation and application of graphene oxide modified separation membrane	CN 202,210,109,317 A	27
Reverse osmosis composite membrane and method for manufacturing reverse osmosis composite membrane	US 201,615,555,916 A	27

laboratory production of GO membranes follows a straightforward and cost-effective process; however, industrial manufacturing must address multiple challenges to maintain consistent product quality, long-term stability, and economic feasibility.

Table 13
Top-10 patents (in terms of cited by patent count) title, application number, and cited by patent count.

Title	Application Number	Cited by patent count
Membranes Comprising Graphene	US 2013/0036,348 W	67
Membranes Comprising Graphene	US 201,314,880,986 A	52
Tunable Layered Membrane Configuration for Filtration and Selective Isolation and Recovery Devices	US 201,313,802,896 A	51
Ultrathin, Molecular-Sieving Graphene Oxide Membranes for Separations Along with Their Methods of Formation and Use	US 201,414,180,724 A	39
Selectively Permeable Graphene Oxide Membrane	US 201,615,380,797 A	38
Layer-by-layer self-assembling oxidized graphene nano-filtration membrane and preparation method thereof	CN 201,410,015,796 A	38
Planar Filtration and Selective Isolation and Recovery Device	US 201,313,803,958 A	33
Polymeric Membranes	US 201,414,193,657 A	33
Compound desalination membrane as well as preparation method and application thereof	CN 201,510,041,252 A	32
Methods For Chemical Reaction Perforation of Atomically Thin Materials	US 201,414,200,195 A	32

Feasibility of GO-based membrane for desalination application in the South-Asian region

South Asia is distinct from other regions in several key aspects that directly influence the feasibility of applying advanced desalination technologies such as graphene oxide (GO) membranes. South Asian nations, including India and Bangladesh and Pakistan and Sri Lanka, operate with limited desalination capabilities because they lack established infrastructure and effective policy support and face elevated operational expenses [136,137]. The area faces fast population expansion, severe water scarcity, restricted land availability, critical energy, and food security problems because of inadequate water resource management and dependence on fossil fuels [138–141]. Economic levels in South Asia are generally lower than in more industrialized regions, with limited internal investment capacity, making international funding and public-private partnerships essential for water and sanitation improvements [142,143]. Policy environments in South Asia often lack the comprehensive incentives and regulatory support seen in countries like the USA and China, resulting in higher costs for implementing new technologies [137].

Furthermore, the region's water management is complicated by competing demands from agriculture, industry, and domestic use, as well as by the impacts of climate change, such as shifting rainfall patterns and glacial melt [144,145]. South Asia offers suitable conditions for solar-powered desalination because of its climate and water scarcity, but several obstacles need to be addressed. The GO membrane technology will thrive in this region when the government backs it through renewable energy funding and international collaboration [146–148].

Conclusion

A complete analysis of GO-based membranes for desalination application research progress and forecast, and real-world technological development has been performed in this study. Both aspects of bibliometric analysis: performance analysis and science mapping, have been performed. Performance analysis has been conducted based on articles, authors, journals, institutions, and countries to understand citation and publication-related metrics. Both the MTCD and MTCY values peaked in 2015, indicating that articles published during that year are the most influential on our topic of investigation. The author Huang Aisheng is the most influential one, considering all the metrics analyzed except the m-index. In contrast, the author Chen Liang has been the most influential, considering the m-index. The journal "Desalination" has been identified as the most influential, considering the number of articles, percentage contribution (%) to total publications, h-index, TGCS, and TLCS. In contrast, the "Journal of Materials Chemistry A" has been identified as the most influential one, considering average TLCS per article and CiteScore. However, the journal ACS Applied Materials and Interfaces has been recognized as the most effective one. Tiangong University is the most effective one in terms of number of articles and percentage contribution (%) to total publications, while the Ocean University of China has been the most influential in terms of TGCS, the Monash University has been the most influential in terms of TLCS, and the Beijing University of Chemical Technology has been the most effective in terms of average TLCS per article. China is the most dominating country in terms of all the metrics except average TLCS per article, according to which, the United Kingdom is the most influential one in our investigated topic. In the burst keywords analysis, the trigrams "water flux performance," "sodium chloride rejection," "forward osmosis system," "ion selectivity mechanism," and "water filtration efficiency" have been determined to be the research hotspots. AI-derived models segmented the dataset into two distinct topics: "Graphene Oxide-Enhanced Nanocomposite Membranes for Desalination," and "Cross-Linked and Layered Graphene Oxide Membranes for Advanced Desalination." Among the two modelled topics, research forecasting results revealed that research on "Cross-Linked and Layered Graphene Oxide Membranes for Advanced Desalination" is expected to grow in the future. From the analysis of the patents, it has been found that patent publication over time on GO-based membranes for desalination applications is not steadily increasing. Among the top patent applicants in our investigation topic, Nitto Denko Corporation has ranked first. The United States ranks 1st and China ranks 2nd in terms of patents by jurisdiction. Among the top owner list, Ide Water Technologies LTD and Membrane Recovery LTD have ranked first jointly. The scientists Kitahara Isamu, Lin Weiping, Wang Peng, and Yamashiro Yuji have jointly ranked 1st in terms of the number of patents published in our investigation topic. The top-cited patents, along with their patent application number, are provided to give the readers an overview of the real-world application of GO-based membranes for desalination. Industrialization challenges of GO-based membrane for desalination applications are elaborately discussed to depict the possible challenges in large-scale fabrication or application of GO-based membranes for desalination. Lastly, feasibility studies of GO-based membranes for desalination applications showed promise in the South Asian region. This work is expected to provide deep and valuable insights into all aspects of GO-based membranes for desalination applications, both research progress and real-world technological implementation.

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CRediT authorship contribution statement

Md. Saiful Islam: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shreyoshi Mazumder:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sadit Bihongo Malitha:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Md. Zahangir Alam:** Writing – review & editing, Validation, Supervision. **A. M. Sarwaruddin Chowdhury:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ceja.2025.100934.

Data availability

The data supporting this article has been included in **Supplementary Document 1, Supplementary Document 2, and Supplementary Document 3.** The "R" scripts and Python scripts used in this study are included as a part of the supplementary information.

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