

# Journal of Agricultural Sciences Research

ISSN 2764-0973

vol. 6, n. 1, 2026

## ... ARTICLE 6

Data de Aceite: 10/03/2026

# BIBLIOMETRIC ANALYSIS OF THE HUMIDIFICATION-DEHUMIDIFICATION DESALINATION SYSTEM: TRENDS AND OPPORTUNITIES.

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**Abstract:** The growing water shortage, driven by population growth and industrialization, threatens to affect two-thirds of the world's population by 2030. Desalination is a solution that converts saline water into drinking water, with lower energy consumption and low environmental impact. Among desalination technologies, the humidification-dehumidification (HDH) system has attractive potential in terms of efficiency and applicability in regions with limited water resources. The objective of this study was to conduct a bibliometric analysis to show the development and trends of scientific articles published on HDH systems during the period from 2000 to 2023, analyzing trends, authors, and topics researched. A descriptive PRISMA methodology was used. From this, a significant increase in the publication of articles was observed, peaking in 2022, with a majority of articles in the areas of engineering and environmental sciences. In addition, searches for key terms (air bubble, spray evaporation, exergy, and cooling) are discussed, reflecting a growing interest in improving energy efficiency and distilled water production capacity. Furthermore, the collaborative analysis provided a multidisciplinary and international approach. The study highlights trends and opportunities for future research in HDH, such as the combination of advanced optimization technologies and the development of systems adaptable to specific conditions. HDH technology is a tool for addressing the global water crisis, contributing to significant advances toward sustainability.

**Keywords:** Desalination, Water scarcity, Energy efficiency, Humidification-dehumidification (HDH), Sustainable technology.

## Introduction

The availability of fresh water is increasingly limited due to population growth and the uneven distribution of water resources. Globally, it is estimated that by 2030, two-thirds of the population will face water scarcity. In Mexico, this situation is particularly critical, as 70% of water resources are located in the south, while the northern and central regions, where the majority of the population lives, suffer from severe shortages (Luna & Grieger, 2015). According to the National Water Commission (CONAGUA), nearly 15 million Mexicans lack access to drinking water, and projections show that demand could exceed supply in the coming years without better water management (Conagua, 2018). It is therefore imperative to urgently address the critical challenges related to water scarcity in order to ensure sustainable and stable development, protecting both human health and ecosystems, and promoting socioeconomic progress in countries. In the face of this crisis, desalination offers a viable solution for obtaining drinking water from saline sources, especially in coastal and arid regions (Martínez-Granados et al., 2022). Humidification-dehumidification (HDH) technology stands out among desalination options for its ability to operate with renewable energy and adapt to different scales, facilitating the sustainable extraction of drinking water from seawater (Lu et al., 2022). This approach may be key to improving water security in Mexico and other countries at high risk of scarcity.

Among the various desalination technologies, the HDH system is a promising and sustainable option due to its efficiency in removing salt from water through heat and mass transfer (Ifras Zubair et al.,

2020). Unlike physical, chemical, or biological desalination technologies, the HDH system is relatively simple, low-cost, and highly adaptable to local conditions, making it ideal for application in areas with limited water and economic resources (Santosh et al., 2022). Advanced HDH systems have demonstrated water recovery rates of over 50% through innovative brine recycling methods (Capocelli et al., 2018). In terms of energy efficiency, studies on HDH systems integrated with absorption cooling and solar energy show remarkable efficiency, managing to produce water at a rate of 0.58 m<sup>3</sup>/h and cooling of 28 t/h. This system achieved competitive production costs of \$2.88/m<sup>3</sup> of water and \$0.135/ton of cooling under conditions of high solar radiation (Baniasad Askari & Shahsavari, 2022). Furthermore, although water obtained through reverse osmosis has a high cost of €0.2284/m<sup>3</sup>, it remains a viable and profitable option for agriculture compared to other sources. In practice, reverse osmosis water yields an annual profit of €12,268, exceeding the profit obtained with surface water (€11,152) and significantly higher than that achieved with brackish water from wells (€3,634). This profit is due to the high production made possible by the use of high-quality water, which offsets the higher initial cost, demonstrating its value in intensive agricultural production systems (Zarzo et al., 2013). Although water obtained through reverse osmosis is a viable and profitable alternative for agriculture, especially for high-value crops, the high cost of production limits its long-term application in regions with budget constraints. In this context, humidification-dehumidification (HDH) systems emerge as a promising alternative for water production in agricultural areas. These characteristics not only promote their imple-

mentation in rural communities and coastal areas, but also support their integration with renewable energy sources, making the HDH system an efficient, economical, and sustainable alternative for the production of drinking water in resource-limited environments (Elsafi, 2017).

Although there are numerous reviews on HDH technology, there is a perceived lack of comprehensive understanding of research trends and collaborations in this field (Elsaid et al., 2020; López-Serrano et al., 2020; Mancuso et al., 2019; Martínez-Alvarez et al., 2016). Previous reviews have addressed technical aspects of HDH, but a comprehensive analysis of publication patterns, geographical contributions, and the impact of international collaboration is still lacking. Recent advances have focused on optimizing heat and mass transfer, a critical aspect that improves the low efficiency of traditional HDH systems (He et al., 2018a). In addition, integration with technologies such as solar energy and multi-stage systems has been shown to increase performance and reduce operating costs (Ortega-delgado & Palenzuela, 2022). While these innovations promise improved efficiency and reduced environmental impact, HDH technology still faces challenges in brine management and energy consumption optimization (Wu et al., 2019). These factors reinforce the need for a bibliometric analysis to identify emerging trends and areas of HDH research that need further development.

The objective of this study was to conduct a bibliometric analysis of the scientific literature on HDH desalination worldwide, in order to identify the evolution of publications, international collaborations, and scientific contributions. The evolution of publications per year was analyzed, and pat-

terns of emerging trends, countries leading research contributions, recent advances, and major knowledge gaps in HDH desalination were identified.

## Methodology

The methodology applied is descriptive with a qualitative approach. It was based on the methodological design suggested by Preferred Reporting Items for Systematic Reviews and Meta-Analyses – PRISMA (Liberati et al., 2009; Urrútia & Bonfill, 2010). The methodological design used is descriptive with a qualitative approach consisting of five stages. The first stage is based on bibliographic compilation, the second stage on searching for keywords that best describe the object of study, the third stage filters publications that are in the subject area of interest, the fourth stage consists of a bibliometric analysis, and the last stage corresponds to the discussion of the data found. The bibliometrix library, part of the RStudio software (RStudio, 2022), was used to process the information. Bibliometrics offers a set of quantitative methods that allow for the systematic analysis of scientific and technological literature, facilitating the identification of research trends, as well as the contributions of different countries, institutions, and academics in the field.

## Bibliographic search strategy

Scopus was determined to be the most suitable database for the bibliographic search strategy. This was based on the most recognized and reliable sources of academic references and citations for peer-reviewed studies. Scopus was selected due to its ex-

tensive coverage of high-impact scientific publications, which allowed for a detailed examination of current trends in HDH desalination. The search inclusion and exclusion criteria were established in accordance with those set out by PRISMA. These criteria can be found in the Table 1 .

Using the inclusion and exclusion criteria, a search equation was created that included keywords in the titles, abstracts, and key terms of the articles, as shown in Table 2, initially generating 1,778 publications for analysis. However, after applying progressive filters based on thematic relevance, the analysis focused on publications that exclusively addressed desalination using HDH, resulting in 632 articles. Additional refinements were applied that included specific terms such as “water filtration” and “spray evaporation,” reducing the sample to 163 publications. Finally, by restricting the search to studies focused on “generators” and “brine,” the final set was limited to 52 articles that comprehensively address the current applications of HDH in desalination.

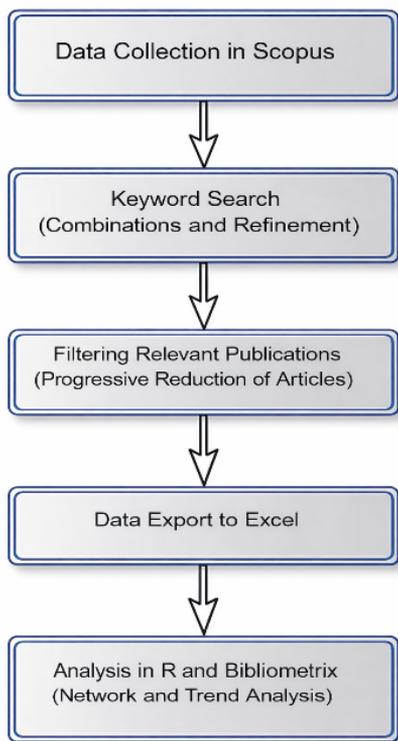
The methodological process followed in this study is illustrated in Figure 4 , which describes each stage, from data collection in Scopus to network analysis in R using Bibliometrix. This diagram summarizes the key steps used to ensure a comprehensive and consistent analysis of trends in HDH desalination.

Type	Criterion
<b>Inclusion</b>	<p>Academic and commercial studies focused on desalination using humidification-dehumidification (HDH) systems.</p> <p>Research exploring improvements in energy efficiency and sustainability in HDH systems.</p> <p>Articles that include terms such as “desalination,” “HDH,” “renewable energy,” and “heat and mass transfer.”</p> <p>Publications from the emergence of HDH until July 19, 2023.</p> <p>Studies analyzing practical applications of HDH in arid and water-scarce areas.</p>
<b>Exclusion</b>	<p>Studies focused on desalination techniques other than HDH (e.g., reverse osmosis).</p> <p>Articles that do not address the impact of HDH on energy efficiency, operating cost, or sustainability.</p> <p>Publications that are not peer-reviewed or lack methodological rigor.</p>

**Table 1** Inclusion and exclusion criteria according to PRISMA methodology

Word group	Keyword combination	Search results
Desalination treatment	TITLE-ABS-KEY (desalination OR seawater) AND TITLE-ABS-KEY (“humidification dehumidification” OR bubble OR “Spray evaporation”) AND NOT TITLE-ABS-KEY (soil OR membrane OR osmosis)	1778
Desalination HDH	(TITLE-ABS-KEY (desalination) AND TITLE-ABS-KEY (“humidification dehumidification”) AND NOT TITLE-ABS-KEY (soil OR membrane OR osmosis))	632
Water filtration	(TITLE-ABS-KEY (desalination) AND TITLE-ABS-KEY (“humidification dehumidification”) AND TITLE-ABS-KEY (“water filtration” OR “spray evaporation”) AND NOT TITLE-ABS-KEY (soil OR membrane OR osmosis))	163
Brine Generator	(TITLE-ABS-KEY (desalination) AND TITLE-ABS-KEY (“humidification dehumidification”) AND TITLE-ABS-KEY (brine OR generator) AND NOT TITLE-ABS-KEY (soil OR membrane OR osmosis))	52

**Table 2** Keyword combinations used and results obtained at each filtering stage, according to the query performed in Scopus (accessed July 19, 2023).



**Figure 4** Flowchart of the methodological process for bibliometric analysis of HDH desalination

## Data preparation

The purpose of this activity was to organize the data so that it met the requirements of the study, allowing for its subsequent processing in the RStudio Bibliometrix library. To meet the requirements of the study and facilitate processing in the RStudio Bibliometrix library, we began by converting the search databases to a format compatible with RStudio. This tool provides robust methods for constructing and visualizing bibliometric networks, allowing for a comprehensive analysis of keywords, author collaborations, and trends in HDH desalination research. The SCOPUS records, originally in .bib format, were converted to .xlsx. Subsequently, duplicate records present in both databases

were removed, following the recommendations of the PRISMA methodology.

## Bibliometric analysis

In the bibliometric analysis, several key aspects were examined to understand research on HDH desalination. Using the bibliometrix library in RStudio, various aspects of the related literature were analyzed. First, documents were classified by type and language to identify the predominant publication formats and the language in which most publications appear. Annual publication trends were also evaluated, which allowed us to observe the growth in the volume of articles on HDH over time. To identify trending topics, the keywords in the articles were analyzed, highlighting the terms most frequently used in different periods, which allowed us to detect patterns in thematic development. Next, scientific production by country and international collaborations were examined by analyzing the affiliation of the authors, which allowed the identification of the main geographical contributions and co-authorship links between countries.

An analysis of emerging keywords was also carried out, measuring the total frequency of each keyword in the articles reviewed, as well as its appearance over time. To analyze thematic relationships, keyword networks were generated that visualized the connections between terms, facilitating the identification of thematic clusters. Similarly, an analysis of collaboration between authors was performed, representing co-authorship networks to identify the most active researchers and groups in the field.

Likewise, the main sources of publication and the contribution of authors were

identified, ranking journals and authors according to the number of publications and the impact of their work. Finally, a network analysis was performed to visualize the relationships between keywords and collaborations, using visualization tools in RStudio that allowed these interconnections to be represented graphically and provided a structured view of HDH research.

## Results and discussion

### Types of documents and languages

The distribution of document types in research on humidification-dehumidification (HDH) desalination reveals that most publications are scientific articles, representing a significant contribution with 1,448 documents, equivalent to 81% of the total. This predominance of articles is followed by conference papers, which represent 14% of publications with a total of 245 documents. Other types of publications make smaller contributions, including reviews (34), book chapters (26), notes (8), conference reviews (7), complete books (4), letters (4), short surveys (2), summary reports (1), and editorials (1). Given the high volume of scientific articles, these were used as the main source for further analysis.

In terms of publication language, English is clearly predominant, used in 1,683 documents, representing more than 94% of total publications. Other languages have a considerably smaller share, with Chinese being the second most used language with 59 publications. Among the other languages, documents were published in Japanese and Russian (7 each), French (6), German (3), Korean and Portuguese (2 each), and

Italian and Turkish (1 each). This distribution suggests that English is the main language of access in HDH literature, facilitating the dissemination and accessibility of research internationally.

### Publication trends

Analysis of scientific productivity on HDH desalination shows sustained growth in article production since 2000, with a notable increase since 2015, a trend that is reported by other researchers (AlMallahi et al., 2024). Figure 5 consists of two sub-graphs: Figure 2 (a), which represents the “Average Citations per Year,” and Figure 2 (b), which illustrates the “Annual Scientific Production.”

Figure 5 (b) shows that the number of publications rose from a single article in 1967 to a significant increase in 1994, with 18 publications in that year. Since 2000, scientific output has grown steadily, with a particularly marked increase since 2015. Over the last decade, approximately 50% of total publications were concentrated in the last five years, indicating a growing interest in HDH technology. Between 2016 and 2020, the number of articles increased by 84.28%, reflecting an upward trend in HDH research, reaching its peak in 2022 with 165 publications. However, in 2021, there was an 11.27% decrease, possibly attributable to the global restrictions imposed by the SARS-CoV-2 pandemic, which impacted research activities in many areas.

On the other hand, the Figure 5 (a) presents the average number of citations per year, which offers a perspective on the influence and relevance of the articles published in each period. Although fluctuations in the average number of citations can

be observed over the years, interest in the topic has stabilized with a constant average of 2 to 4 citations per article in recent years. This behavior suggests that, although the number of publications has grown significantly, the impact in terms of average citations has not followed a linear growth pattern. This may be due to the emerging nature of HDH research, which attracts a growing number of new studies, but whose impact is still being consolidated in the scientific literature.

These results reveal that HDH technology is an emerging area of research and growing interest, considered promising as a sustainable method for desalination. The increase in recent scientific output, accompanied by a moderate average number of citations, reflects that this technology has gained traction and recognition in the scientific community, although its influence is still in a stage of growth and consolidation.

### Trending topics

Figure 6 shows the analysis of emerging keywords in research on HDH desalination from 2000 to 2023. This graph represents the progressive use of different terms in the scientific literature on HDH from 2000 to 2023. Each keyword is located on the vertical axis, while the horizontal axis shows the time in years. The horizontal lines show the period in which each keyword began to gain relevance, extending to the last year of frequent use. The circles superimposed on these lines represent the frequency of occurrence of each term in a specific year, with the size of the circles showing the intensity of use: the larger the circle, the greater the frequency of that term in the HDH literature in that year.

This analysis highlights the thematic growth in HDH, with an increase in the appearance of terms such as “fresh water,” “system productivity,” “packed beds,” and “HDH system,” which underscores the interest in optimizing the efficiency of HDH systems and integrating renewable energies, as seen in terms related to “solar power generation” and “solar collectors.” In addition, technical concepts such as “mass transfer,” “heat transfer,” and “evaporation” reflect a focus on the principles of heat and mass transfer, which are essential for improving performance and reducing operating costs, key aspects for the commercial viability of HDH.

The trend also shows a growing interest in the use of “mathematical models” and “computer simulation” to predict and optimize the behavior of HDH systems, suggesting a shift toward computational design to increase the efficiency and adaptability of these systems in different operating contexts. This reflects an effort in research to make HDH a sustainable and advanced desalination technology.

### Publication by Country and International Collaborations

Figure 7 shows the geographical distribution and temporal behavior of publications on humidification-dehumidification (HDH) desalination in the countries most active in this research. This figure is composed of two sub-graphs: Figure 3 (a), a world map representing the number of documents produced per country, and Figure 4 (b), a line graph showing the cumulative growth of publications in the top five countries from 2007 to 2023. REF\_Ref181055561 \h \\* MERGEFORMAT

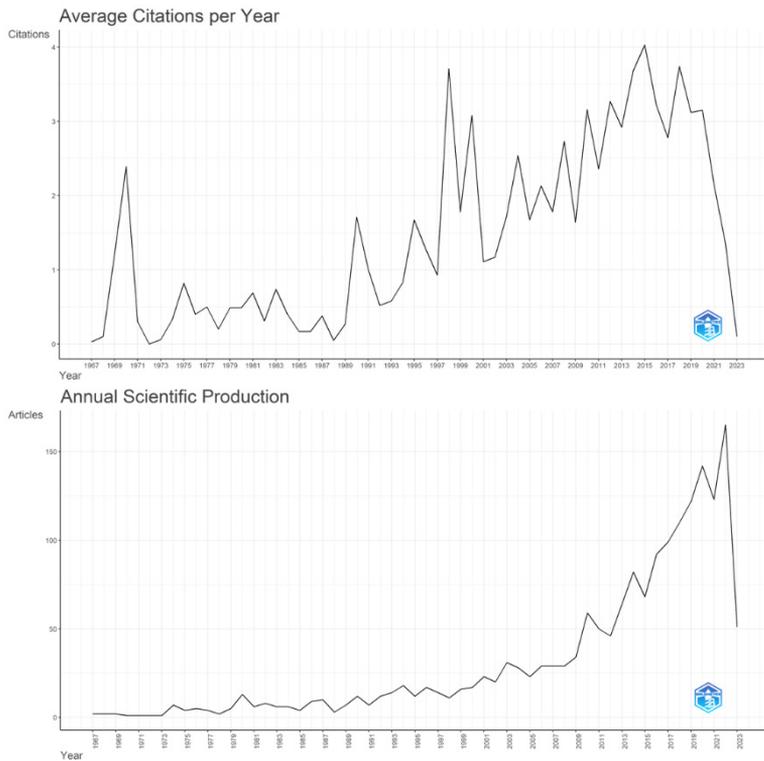


Figure 5 Annual publications and citations on HDH desalination.

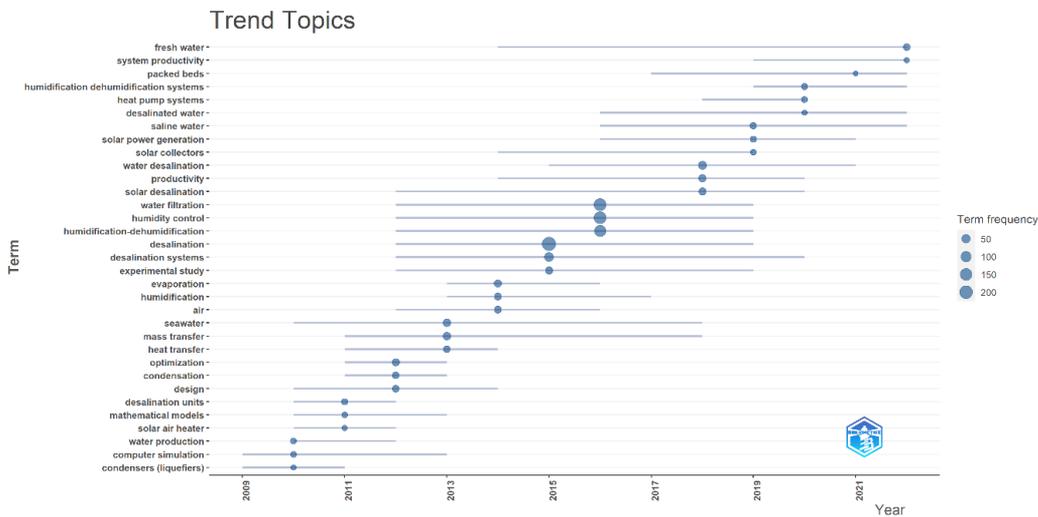


Figure 6 Trending topics in HDH research in recent years

*Figure 7* (a) reveals that Egypt is the leading contributor to HDH research, accounting for 22% of total publications, followed by the United States (14%) and Iran (12%). The notable activity in Egypt (Mahmoud et al., 2019; Mohamed et al., 2021) and other countries with arid climates (Aref et al., 2021) or semi-arid climates such as Saudi Arabia (D. Lawal et al., 2018) and China (He et al., 2018a) reflects an urgent need for sustainable desalination technologies in these regions, where water scarcity is a pressing issue. The interest in HDH in these areas suggests that this technology can offer viable solutions to improve access to drinking water in highly arid conditions (Zarei & Behyad, 2019).

*Figure 7* (b) illustrates the temporal behavior of the number of publications in the five leading countries: China, Egypt, Iran, Saudi Arabia, and the United States. The cumulative growth trajectory shows that, although Egypt and the United States were pioneers in HDH research, China has experienced a notable increase in scientific output since 2007, reaching leadership in recent years (Pereira & Jegatheesan, 2024). This may be linked to China's policies that encourage research and development in sustainability technologies, especially in critical areas such as water security. The trend in Iran and Saudi Arabia also shows sustained growth, which is consistent with the importance of this technology in regions facing water challenges (Alazaiza et al., 2024).

*Figure 7* as a whole also highlights the expansion of international collaborations over the last decade. The presence of co-authorship networks among leading countries, especially between Egypt, the United States, Saudi Arabia, and China, indicates that HDH research efforts are becoming in-

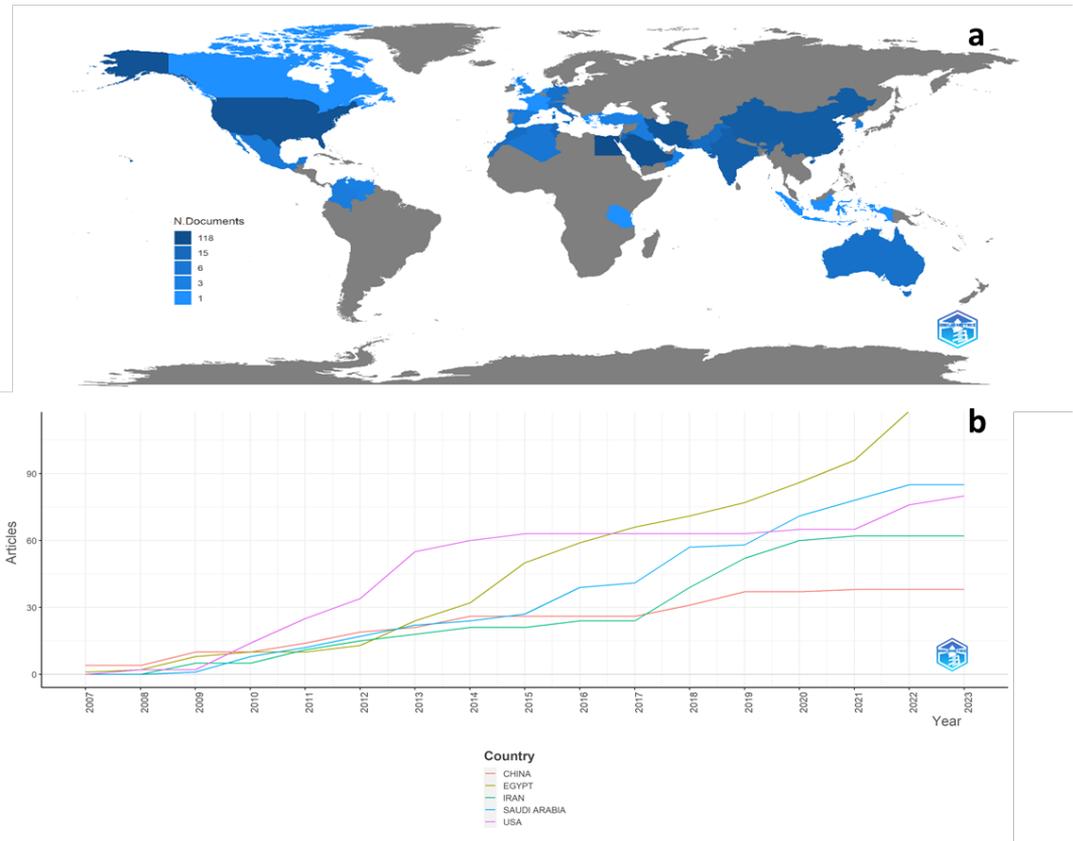
creasingly collaborative. These international alliances facilitate the exchange of knowledge and resources, allowing technological advances in HDH to be adapted to different geographical and socioeconomic conditions. The intensification of these collaborations is crucial for the development of global solutions, as it allows HDH technology to be adapted to the specific needs of each region (Adrián et al., 2020).

These results suggest that HDH technology is becoming increasingly relevant worldwide, not only in terms of scientific production, but also in the formation of international collaboration networks that promote the advancement of the technology (Berana et al., 2024). Research activity in countries vulnerable to water scarcity and collaboration between them reinforce the potential of HDH to mitigate problems of access to drinking water in contexts of water stress (Okasha et al., 2022).

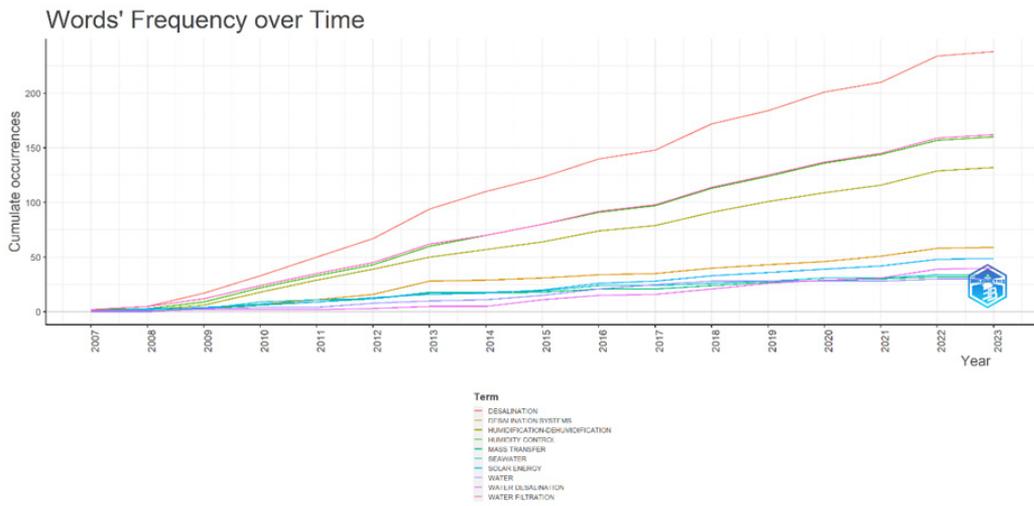
## Emerging HDH research keywords

*Figure 8* presents a detailed analysis of the cumulative frequency of keywords in the field of HDH desalination from 2007 to 2023. This allows us to identify emerging trends and thematic developments in scientific literature. Each line in the graph represents the cumulative frequency of a specific term over time, allowing us to observe the emergence of new topics in the field, as well as their intensity and persistence.

In this work, 1,391 keywords were identified, of which “desalination” and “water filtration” stand out as the most frequent, showing their centrality in HDH research. These dominant keywords are represented by the top lines in the graph, suggesting that desalination in general and water filtra-



**Figure 7** Comparison of research growth trends in major countries.



**Figure 8** Frequency of words over time

tion systems are fundamental components in this field. The cumulative frequency of these terms has grown steadily, giving us an idea of their sustained relevance over the years. In addition, terms such as “humidity control” and “humidification-dehumidification” have shown a considerable increase in frequency in recent years, signaling an emerging focus on the technical aspects of humidity control and efficiency of HDH systems. This focus is aligned with the interest in optimizing the performance of the desalination process, especially with regard to reducing energy consumption and improving system efficiency (Huang et al., 2019; Teixeira et al., 2008). The graph also reveals a growing interest in topics related to the physical processes involved in HDH, such as mass transfer and heat transfer (Sharqawy et al., 2014). The presence of these terms in the literature, although less frequent than the dominant keywords, shows an effort to delve deeper into the fundamental principles of mass and heat transfer, which are crucial for improving the performance of HDH systems and making them more sustainable (Agyekum et al., 2024).

### Keyword network analysis and collaboration between authors

Figure 9 shows a visual analysis of the most frequently occurring keywords in articles and their interrelationships in HDH research. Central themes and interconnected areas in the literature are identified, which is essential for understanding the focus and priorities in the development of this technology. In the network, terms such as “desalination,” “water filtration,” and “humidity control” occupy prominent positions, reflecting their crucial role in HDH technology. With a frequency of 15% for

“desalination,” followed by “water filtration” and “humidity control” (both with 10%), these terms focus primarily on ensuring the production of drinking water through filtration and humidity management processes, which are fundamental pillars of sustainable desalination.

Technical issues related to system optimization are addressed with terms such as “mass transfer,” “evaporation,” and “heat transfer” forming interrelationships. This indicates that research in HDH has been oriented toward improving heat and mass transfer mechanisms, which are essential for increasing system efficiency (Xuening et al., 2015). Optimizing these processes allows for better use of energy resources, thereby reducing operating costs and increasing the amount of fresh water produced, which is fundamental to the commercial viability of HDH technology (He & Han, 2017; Mahdizade & Ameri, 2018).

The figure shows a growing interest in the integration of renewable energies, evidenced by terms such as “solar energy,” “solar power,” and “solar desalination.” This reveals that researchers have been exploring the use of sustainable energy sources to reduce environmental impact and make HDH technology more economical and applicable in regions with high solar irradiation. The incorporation of solar energy into HDH systems represents an alternative for improving the sustainability of the process, especially in remote and arid areas (Faizan et al., 2022).

The graph shows the presence of terms associated with design and experimentation, such as “optimization,” “experimental study,” and “numerical model.” This also indicates a trend toward modeling and experimental analysis, with the aim of optimizing

the operating conditions of HDH systems prior to their implementation (Juwad et al., 2023). The development of numerical models makes it possible to predict the behavior of the system under different configurations, facilitating the design of more efficient installations that are tailored to local needs (El-Ghetany & Khattab, 2016; Saldivia et al., 2021; Zhani et al., 2011). On the other hand, terms such as “productivity,” “condensation,” and “cooling” underscore efforts to increase the productivity and efficiency of HDH systems (Elattar et al., 2020; Zhang et al., 2018). The goal is to maximize the amount of fresh water generated, while emphasizing cooling and condensation technologies (D. U. Lawal & Qasem, 2020).

This indicates that HDH is not limited to desalination alone, but is expanding into technical and design areas that seek to optimize the efficiency and sustainability of the process (Breckle, 2009). The keyword network reflects a complex structure in which multiple technical and environmental aspects converge, guiding the future development of this technology towards a comprehensive and sustainable approach (Abdelmoez et al., 2019).

In terms of collaboration between authors, Figure 10 shows the patterns of collaboration between different researchers in the field of HDH. This network analysis reveals collaborative connections, in which prominent authors such as Zubair, Lienhard, and Antar emerge as central figures, leading the development and dissemination of knowledge in this area. Their position in the network suggests that they have played a key role in connecting different research groups, acting as links between various co-authorship subnetworks.

The structure of the network reflects a collaborative and multidisciplinary approach, where the existence of international connections suggests that the development of HDH solutions is not limited to a single group or region, but is nourished by the global exchange of knowledge and perspectives. The links between authors, represented by the lines in the diagram, show that HDH research is a collective effort that integrates diverse disciplines and methodological approaches. This broad and diverse collaboration has enabled innovation in the field by combining the resources and experiences of researchers from different institutions and countries.

The presence of distinct clusters in the network also points to areas of specialization within HDH technology, with research groups focusing on specific topics such as energy efficiency and energy- (He et al., 2018b), system design (Elhashimi et al., 2022), and renewable energy integration (Abdelmoez et al., 2019). The formation of these collaborative clusters suggests that, although HDH research is largely collaborative, there are specialized sub-areas that are advancing in parallel.

Figure 11 presents an analysis of collaboration between authors, highlighting the formation of multiple research clusters. These clusters reflect groups of authors who collaborate on a recurring basis, suggesting specialization in specific subtopics of HDH technology. Such as heat and mass transfer optimization, solar energy integration, water filtration system design, and condensation efficiency improvements. This organization into collaborative networks shows that, although HDH research is multidisciplinary and cooperative in nature, there are areas of specialization that advance in parallel. The



Figure9 Visualization diagram of the co-keywords with the highest incidence in the database (n=163)

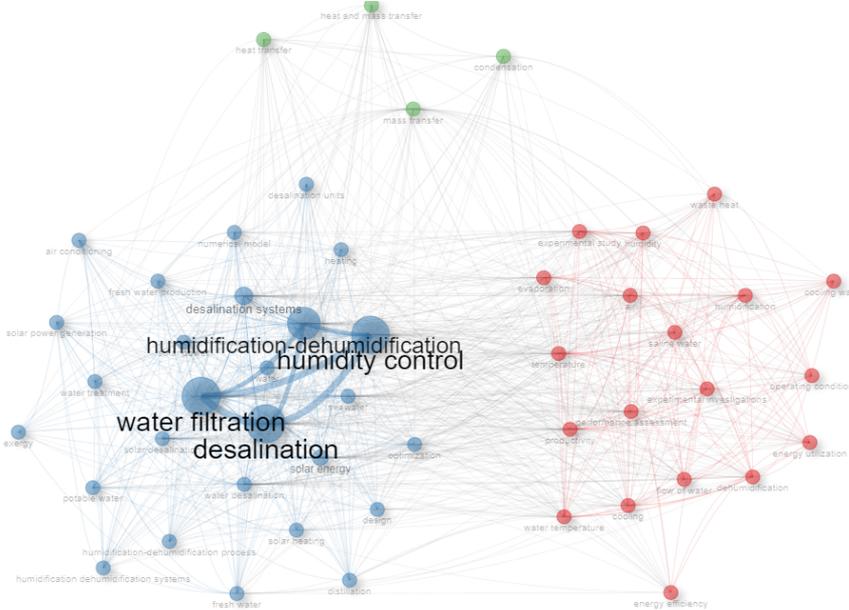


Figure10 Network analysis diagram based on indexed keywords

coexistence of these clusters contributes to the development of specialized knowledge in specific areas, while promoting global advances in HDH desalination technology.

This analysis shows how shared efforts and simultaneous specialization in areas such as energy efficiency, humidity control, and the development of new materials strengthen the field of desalination, supporting both specific innovation and the development of solutions applicable to different contexts.

### Leading journals and author contributions

Research on HDH has been disseminated through a wide range of journals, totaling 71 publications in various fields of study. The journal *Desalination* stands out as the main source of publications in this area, accounting for 29.4% of the total articles and accumulating 48.9% of the citations, consolidating its role as the most influential medium for the dissemination of research on HDH. **Table 3** shows that *Desalination* has published 47 articles since 2009, with an SJR factor of 1.632 and an average of 18.72 citations per article, demonstrating its importance in the field. The second most influential journal, *Applied Thermal Engineering*, has 9 articles and an average of 25.66 citations per article, making it relevant in the field of thermal engineering applied to HDH.

Other journals, such as *Energy Conversion and Management* and *Energy*, have also contributed significantly, publishing research that explores energy efficiency and HDH system design, key areas for the sustainable development of this technology.

These publications, although smaller in volume, have a high average number of citations, making a considerable impact in the field. This pattern of publication in high-impact journals underscores the multidisciplinary nature of HDH technology, which encompasses topics in engineering, materials science, and renewable energy.

In terms of author contributions, the **Table 4** highlights the most active and cited researchers in the field of HDH, including Syed M. Zubair of King Fahd University of Petroleum and Minerals in Saudi Arabia and John H. Lienhard V of the Massachusetts Institute of Technology in the United States. Zubair, with 17 articles and a total of 1,219 citations, ranks as the most influential author, followed by Lienhard, who averages 81.3 citations per article, indicating the high quality and relevance of his research. This group of authors not only contributes to academic production but also leads international collaboration networks, promoting a global and multidisciplinary approach to the development of solutions for desalination using HDH.

In addition to these authors, collaboration between institutions in different countries, particularly between Saudi Arabia, Egypt, and the United States, reflects the international nature of HDH research. Active researchers not only publish in influential journals but also contribute to the advancement of the field by exploring emerging topics, as seen in the keyword frequency discussed in the **Table 5**. This collaborative approach and exchange of knowledge across disciplines suggest sustained progress in HDH technology, adapting it to contemporary challenges of sustainability and efficiency.



Author	Articles	Citations	Average citations <sup>1</sup>	H index <sup>2</sup>	City	Affiliation <sup>3</sup>	First article	Last article	ORCID
Zubair, Syed M.	17	1219	71.7	14	Saudi Arabia	King Fahd University of Petroleum and Minerals,	2010	2021	<a href="https://orcid.org/0000-0001-6994-0242">https://orcid.org/0000-0001-6994-0242</a>
Lienhard V, John H	11	894	81.3	10	United States	Massachusetts Institute of Technology	2010	2014	<a href="https://orcid.org/0000-0002-2901-0638">https://orcid.org/0000-0002-2901-0638</a>
Antar, Mohamed A.	10	665	66.5	8	Saudi Arabia	King Fahd University of Petroleum and Minerals	2010	2020	<a href="https://orcid.org/0000-0003-1000-3662">https://orcid.org/0000-0003-1000-3662</a>
Kabeel, A. E.	10	495	49.5	9	Egypt	Tanta University	2013	2022	-
El-Said, Emad M.S.	7	325	46.5	7	Egypt	Faculty of Engineering, Damietta	2013	2022	<a href="https://orcid.org/0000-0002-4247-5763">https://orcid.org/0000-0002-4247-5763</a>
Elattar, Hassan Fawzy	7	360	51.5	6	Egypt	Faculty of Engineering in Shubra , Cairo	2015	2020	-
Fouda, A.	7	360	51.5	6	Egypt	Mansoura University, Mansoura	2015	2020	-
Nada, Sameh A.	7	360	51.5	6	Egypt	Benha University	2015	2020	<a href="https://orcid.org/0000-0002-1975-7543">https://orcid.org/0000-0002-1975-7543</a>
Amidpour M	6	225	37.5	6	Iran	K. N. Toosi University of Technology	2009	2013	<a href="https://orcid.org/0000-0003-2073-6106">https://orcid.org/0000-0003-2073-6106</a>

**Table 4** Main characteristics of the most active authors in HDH research.

## Network analysis

Figure 12 provides a detailed analysis of the network of citations (CR), authors (AU), and keywords (DE) in HDH research, showing the interconnection between studies and topics in this field. In the left panel, the citations column (CR) reveals which studies are most referenced, showing the influence of certain research on the theoretical and practical development of HDH technology. The works of prominent authors such as Syed M. Zubair and Mohamed A. Antar appear frequently, reflecting their central position in HDH literature. These authors, visible in the center column (AU), are recognized for their contributions in key areas such as thermal optimization and HDH system design, underscoring their role as leaders in this field.

The keyword column (DE) on the right-hand side illustrates the most recurring terms in HDH research, with “desalination,” “humidification-dehumidification,” and “solar desalination” standing out as predominant terms. This focus on specific keywords suggests that researchers are oriented toward improving desalination efficiency through HDH processes, with a particular emphasis on harnessing renewable energies such as solar energy. The interrelationship between authors and keywords highlights the multidisciplinary and collaborative nature of this research, with researchers sharing common goals in terms of sustainability and energy efficiency. The themes of system optimization and sustainability stand out, with a shared and consolidated focus on improving HDH technology to address problems of access to drinking water in areas with scarce resources.

## Implications and limitations

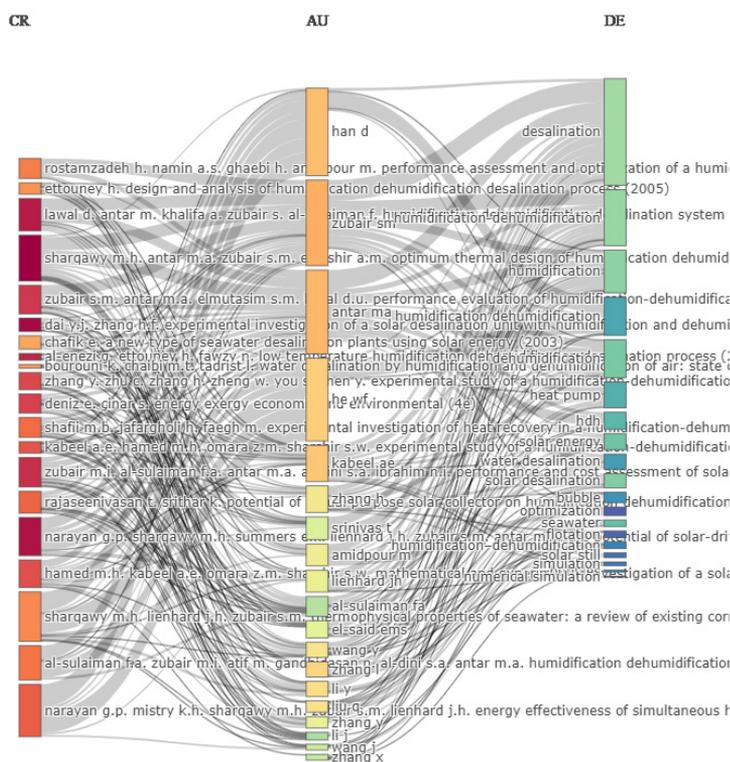
The bibliometric analysis of HDH desalination technology conducted in this study offers important insights into current and future trends in the field. Unlike research on more established desalination technologies, such as reverse osmosis, the study reveals that HDH research is still limited, highlighting significant potential for expansion. This research gap represents an opportunity for future studies to delve deeper into specific aspects of HDH, such as energy efficiency, integration with renewable energy sources, and process optimization. Furthermore, the patterns of collaboration between authors and institutions observed in the analysis suggest that progress in HDH can greatly benefit from more robust and multidisciplinary research networks, facilitating knowledge exchange and innovation in the field.

The findings of this study underscore the need for improvements in the management and efficiency of HDH technology. Emerging research trends, especially in terms of humidity control, mass transfer, and solar energy, could guide the development of more sustainable HDH systems adapted to specific contexts, such as regions with water scarcity. Institutions and researchers can use this information to direct their efforts toward areas of high relevance and potential impact, optimizing the use of resources and maximizing social and environmental benefits.

However, this study has limitations. The reliance on a single database, Scopus, means that the results may not fully capture the landscape of HDH research, potentially excluding relevant articles indexed in other sources. Furthermore, due to the dynamic nature of HDH technology, certain articles

Place	Keyword	Occurrences
1	Desalination	238
2	Water filtration	162
3	Humidity control	160
4	Humidification/dehumidification	132
5	Desalination system	59
6	Solar energy	49
7	Water desalination	40
8	Mass transfer	32
9	Evaporation	28
10	Solar desalination	24

**Table 5** Total link strength of the 10 most frequently occurring keywords.



BIBLIOMETRIC ANALYSIS OF THE HUMIDIFICATION-DEHUMIDIFICATION DESALINATION SYSTEM: TRENDS AND OPPORTUNITIES.

**Figure 12** Network analysis of citations, authors, and keywords in humidification-dehumidification (HDH) research

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may be outdated, affecting the representativeness of some topics in the analysis. Future studies could benefit from a wider variety of sources and constant updating of the database to reflect ongoing progress in HDH technology.

## Future research opportunities in HDH

The bibliometric analysis of HDH technology reveals several promising areas for future research that can strengthen its application in sustainable desalination. First, although HDH demonstrates efficiency and adaptability, specific gaps requiring further research have been identified. The integration of advanced heat and mass transfer technologies, such as energy recovery and the use of innovative materials, appears to be a priority for improving energy efficiency and reducing the operating costs of HDH systems.

In addition, comparative studies evaluating the performance of HDH against other desalination techniques, such as reverse osmosis and membrane distillation, are suggested as a way to establish the conditions under which HDH offers significant advantages. This comparison could clarify the optimal scenarios for its implementation, highlighting its value in terms of efficiency and sustainability. Similarly, the exploration of hybrid systems, which combine HDH with renewable energy sources, especially solar, is proposed as a path toward autonomous desalination solutions suitable for regions with limited resources.

The development of simulation and performance prediction models is also identified as a fundamental need, as these would facilitate the adaptation of HDH to various

operating conditions and scales of application. Research in modeling, combined with economic and cost- r production analyses, provides a critical basis for decision-makers to evaluate the viability of HDH in specific environments. Finally, the importance of studying the management of brine waste generated by the HDH process is recognized, with a focus on environmentally responsible reuse or disposal methods.

## Conclusion

This bibliometric study provides an overview of the evolution of research into humidification-dehumidification (HDH) desalination, highlighting the main lines of research, emerging trends, and existing gaps. Through the analysis of 163 publications between 2007 and 2023, there is a growing interest in HDH as a sustainable desalination technology, especially in countries with arid climates and water scarcity, such as Egypt, the United States, and Iran. This increase in scientific output reflects greater social and political awareness of the need for sustainable solutions to environmental challenges and water scarcity exacerbated by climate change.

The findings show that the main research topics include solar energy integration, humidity control, mass transfer, and the implementation of heat pump systems, suggesting a focus on improving the efficiency and sustainability of HDH systems. Analysis of journal contributions reveals that Desalination and Applied Thermal Engineering lead the field in publications, lending scientific relevance to these studies in high-impact journals. In addition, influential authors such as Zubair, Lienhard, Antar, and Kabeel have played a significant role, contributing a

considerable percentage of the total articles published.

The review highlights the potential of HDH as an emerging technology in desalination, with opportunities to optimize its efficiency and reduce costs. This study aims to guide researchers and institutions in identifying priority areas and formulating research strategies that address the technical and economic challenges facing HDH, thus contributing to the development of sustainable solutions in water resource management in regions with high levels of water stress.

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