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A comprehensive bibliometric and patent landscape of solar desalination: Trends, innovations, and global contributions

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Abstract. The global water scarcity crisis, driven by increasing demand and declining freshwater supplies, necessitates innovative solutions like solar desalination, which uses abundant seawater and solar energy to produce fresh water. This study applies a bibliometric analysis to solar desalination, revealing a sharp rise in publications and patents after 2010. SCOPUS data identifies six main research areas, including "Engineering" and "Environmental Science." India leads in publications with 1,668, while China dominates patent filings and academic influence. Patent data from PATSNAP shows that 71% of patents are inventions, with 33% still active. Significant innovations include a plasmon-enhanced solar desalination device, as noted in the most cited publication, while solar-driven inter-facial evaporation is emerging. Key patents highlight agile light control for solar desalination and a multi-effect distillation system that optimizes energy use. These breakthroughs not only improve efficiency but also offer adaptable, sustainable solutions to address global water and energy challenges.

1 Introduction

Water scarcity is a significant issue in many countries, especially in North Africa and the Middle East, where growing populations strain limited water resources. In 2019, the World Resources Institute reported that 17 countries, representing a quarter of the global population, faced "extremely high" water stress, projected to rise to 33 countries by 2040 [1]. To address this, many countries rely on desalination, which separates salt from seawater to produce fresh water. Desalination methods include thermal and membrane processes. Thermal desalination involves heating salted water and cooling the vapour to obtain fresh water, using techniques such as multi-stage flash (MSF) and multi-effect desalination (MED) [2–4]. Membrane desalination includes electrodialysis (ED) and reverse osmosis (RO), which uses high pressure to push saline water through a semi-permeable membrane [5]. However, desalination is costly and energy-intensive, with membrane systems being more energy-efficient than thermal methods [6] . For example, energy needed to desalinate 1m³ of water ranges from 14.45-21.35 kWh/m³ for MED to 2-4 kWh/m³ for RO [7–9]. Renewable energy sources,

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particularly solar, offer potential solutions for sustainable desalination. Solar desalination directly harnesses sunlight to drive the desalination process, eliminating dependence on external power grids and reducing carbon emissions. Unlike wind- or wave-powered desalination, solar energy is abundant, especially in regions most affected by water scarcity, making it a highly viable alternative. Furthermore, solar desalination can be integrated with advanced technologies such as solar stills or photovoltaic-powered RO systems, offering decentralized, scalable, and cost-effective solutions for remote or underdeveloped areas. In 2023, the desalination operating capacity was 109.22 million m³/day, with 4.4 million m³/day of new capacity added. Despite its importance, high energy consumption remains a challenge [10]. Renewable energy sources, particularly solar, offer potential solutions for sustainable desalination. Over 300 million people depend on desalination for daily water needs, making it a critical area of focus [11]. The present study assesses patent and scientific data of solar desalination using a bibliometric approach, evaluating publications indexed in Scopus and PatSnap databases. Scopus, a European bibliographical database, provides excellent coverage of African countries, while PatSnap is an analytics patent tool using AI to analyse data from several patent databases worldwide, including IP5, WIPO, and EPO, representing over 177 million patents.

2 Methodology

Bibliometric uses statistical and mathematical methods to explore scientific or patent databases through qualitative and quantitative analysis of publications data, examining relationships between authors, institutions or countries. It uncovers research and innovation structure, emerging trends, and collaboration patterns, within a specific domain [12–14]. For this study, publications on solar desalination were collected using keywords such as "solar desalination," "solar still," and more specific terms like "multi-stage flash distillation" combined with "solar energy." The keyword selection process was iterative: preliminary searches using obvious terms were followed by refinements based on suggestions from the database, ensuring a comprehensive search while minimizing irrelevant results (noise) and missing relevant publications (silence). Searches were conducted using "advanced search" in the fields "Title, Abstract, Keyword" on the Scopus database [14] and “Title and Abstract” on PatSnap [15]. In Scopus, publications are categorised using the All Science Journal Classification (ASJC) into twenty-seven major fields [16]. Patent analysis uses the International Patent Classification (IPC) [17] and the Cooperative Patent Classification (CPC) [18], hierarchical systems classifying patents and utility models by technological fields . This analyse calculates bibliometric indicators such as publication count, citations, and international collaboration, from extensive unstructured data, effectively mapping cumulative publications and capturing evolutionary trends with precision. Some indicators, like publications, are simple to obtain, while others, such as Field-Weighted Citation Impact (FWCI), which compares citations with global averages, are more complex[19]. FWCI is calculated as follows:

$$FWCI = \frac{1}{N} \sum_{i=1}^{N} \frac{c_i}{e_i} \tag{1}$$

Where N is the publication count, ci represent citations of publication i in the publication year plus three years and ei is the expected citations received by all similar publications in the same period. When the similar publication is assigned to more than one subject area, the harmonic mean is used to determine ei. An FWCI of 1.00 indicates citations are exactly as expected based on the global average for similar publications, an FWCI > 1.00 means the output is more cited than expected, and vice versa. For instance, if a publication in solar desalination receives 50 citations ($N = 1, c_i = 50$) and similar studies in the same field and timeframe are expected to receive 40 citations ($e_i = 40$), the FWCI for that publication would be 1.25 (50/40), meaning it is cited 25% more than expected. Conversely, if the expected citations were higher (e.g. $e_i = 60$), the FWCI would be 0.83, indicating it is cited less than expected.

3 Results and discussion

3.1 Literature analysis

3.1.1 Scholarly output type

The database Scopus, inquired between May and July 2024, revealed over 6,927 publications on solar desalination up to 2023, constituting 21% of all desalination literature in that period. Interest in solar desalination dates back to the first indexed paper in 1952 [20]. Publication numbers fluctuated significantly and grew slowly until 2010, after which they increased dramatically. Notably, 80% of these publications were produced between 2010 and 2023, making this period the focus of the present study. Of these publications, only 23% were open access. Journal articles accounted for 72% of the total, followed by conference papers (14.6%) and reviews (8%). English was the predominant language at 97.7%, followed by Chinese (2%) and Spanish (0.1%).

3.1.2 Scientific production over time

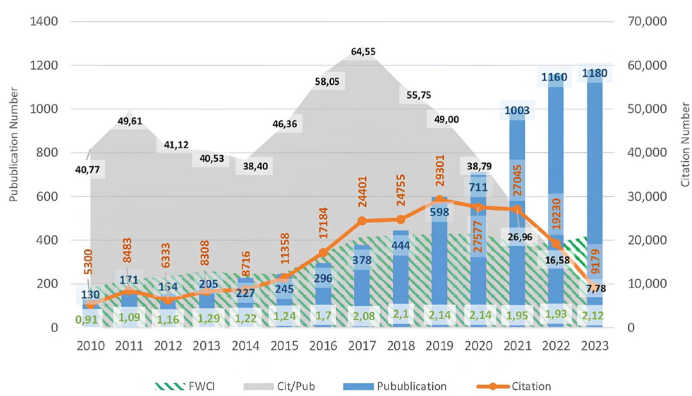

Figure 1. Scholarly output on solar desalination - Scopus 2010-2023

The corpus of 6,927 documents, published between 2010 and 2023, accumulated a total of 217,991 citations. Annual citation counts rose consistently, peaking between 2016 and 2021. The most cited publication was a Chinese-American collaboration titled: "3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination" [21] published in Nature Photonics, in 2016. The average citation per publication is approximately 31.47, reaching a high of 64.55 in 2017, followed by a sharp decline after 2019 (Figure 1). This decline likely stems from a rise in publications and a relative drop in citation rates, possibly linked to the COVID-19 pandemic. The Field-Weighted Citation Impact (FWCI) exceeded 1.00 after 2010 and remained above 1.00 throughout the period, indicating that the scientific literature in this field is cited more frequently than the global average.

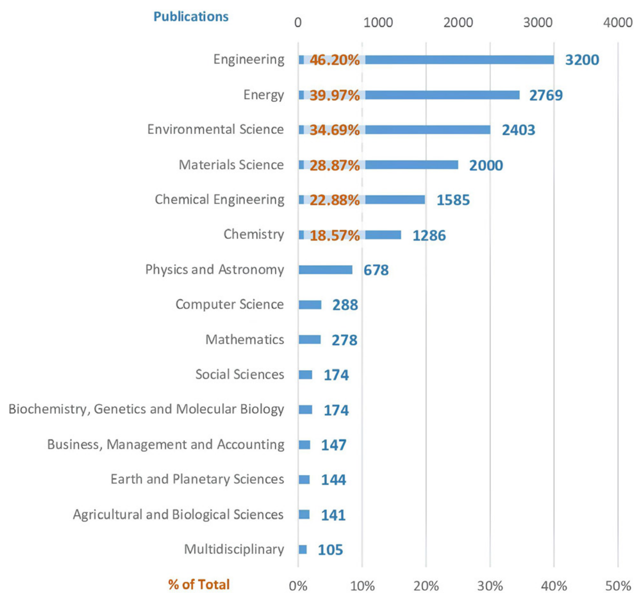

Figure 2. Distribution of solar desalination papers by subject areas Scopus 2010-2023

3.1.3 The distribution of research areas

The 6,927 documents spanned twenty-four of ASJC subject areas in Scopus. As shown in Figure 2, "Engineering" was the most prominent subject area during the studied period, with 3,200 publications, representing 46.2% of the studied corpus. The second most important area was "Energy," with 2,769 publications (39.97%), followed by "Environmental Science" with 2,403 publications (34.69%) and "Material Science" with 2,000 publications (28.87%) while "Chemical Engineering" and "Chemistry" contributed 22.88% and 18.57% respectively. 94.14% of the studied corpus is indexed in the top six defined research areas. These areas experienced a remarkable growth of over 400% during the analyzed period. Specifically, 'Energy' and 'Materials Science' saw an exceptional increase of more than 700%, suggesting that current trends in the studied field are likely focused on energy consumption reduction and exploring new materials to enhance performance and lower operational costs.

3.1.4 Keyword analysis

The database uses text mining to identify important keywords, which are then matched against a unified thesaurus to create a standardized list. Figure 3 shows keywords related to solar desalination, visualized using a word cloud, where each keyword is weighted by the number of publications that contain it. The word cloud confirms the quality of the research equation and reveals an important fact: terms like "Distillation" (2800) and "Solar Still" (1894) are more cited than "Water Filtration" (933) and "Reverse Osmosis" (355). This indicates that research in solar desalination is still more focused on thermal processes than

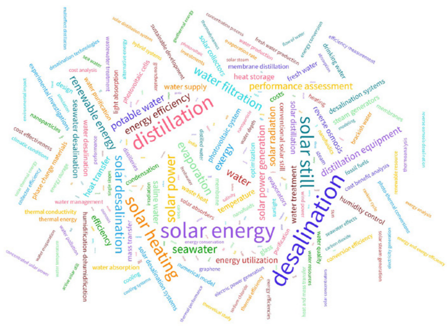

Figure 3. The most used keywords on solar desalination Scopus 2010-2023

on membrane methods. The emphasis on distillation reflects a preference for low-cost technologies that directly harness solar energy to evaporate saline water, minimizing the need for expensive infrastructure and external energy sources. However, despite their widespread use, these systems face limitations in efficiency and daily yield, which could drive future research toward optimization. Potential directions include integrating interfacial evaporation concepts or advanced materials to improve heat transfer. Interestingly, the keyword "Solar-Driven Interfacial Evaporation," though less frequent in the analyzed corpus, saw a remarkable 4500% increase during the study period, reflecting growing interest in this emerging technology.

3.1.5 Countries' characteristics

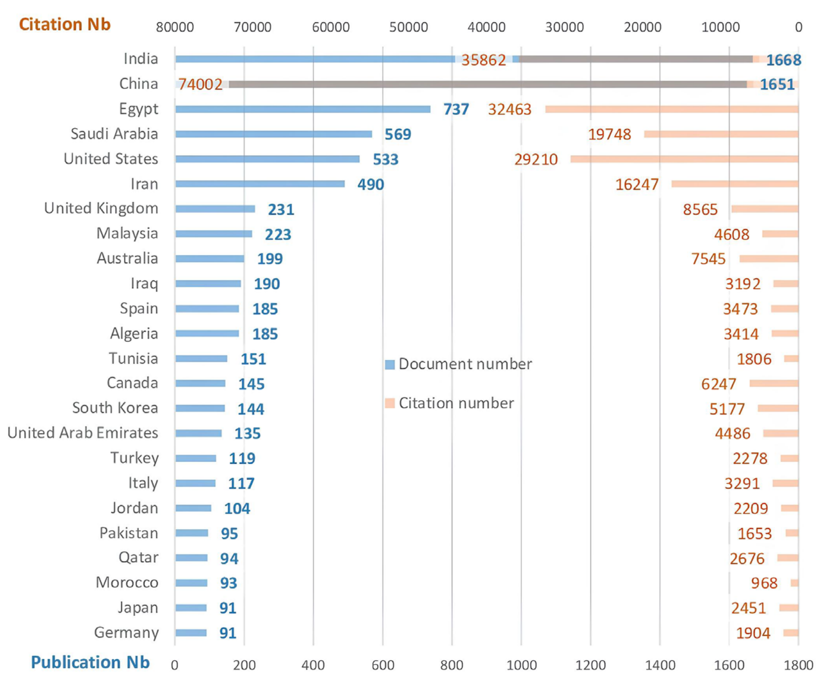

Figure 4. Publications and citations of the most productive countries - Scopus 2010-2023

India and China together hold nearly half of the publications, each contributing 24% of all papers, with 1,668 and 1,651 publications respectively (Figure 4). Although China had 17 fewer publications than India, its publications had the most academic impact, boasting the highest citations count (74,002), which is more than double India's citations (35,862). On the other hand, contrast, Egypt ranked third in both publication count (737) and citations (32,463). The collaboration network graph illustrates the connections between the top 75 countries represented by nodes, with 4,377 collaborative links. The size of each node proportional to the number of publications from that country. The most significant collaborations were between Egypt and Saudi Arabia (209 papers), Egypt and India (152 papers), and China and the United States (118 papers). A QR code (Figure 5) provides access to the online graph

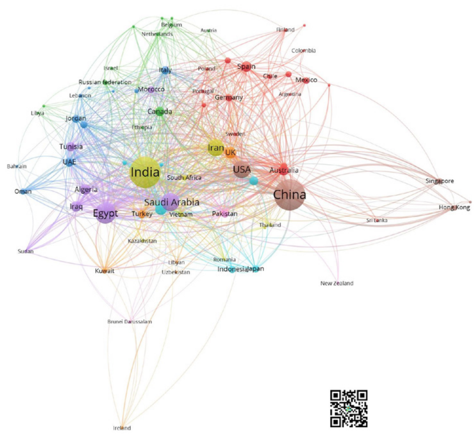

Figure 5. Country collaboration on solar desalination 2010-2023

3.2 Patent analysis

3.2.1 Patent types and legal status

The patent analysis using the PATSNAP tool revealed 5,641 patents published in the field of solar desalination. These patents, grouped into 3,854 patent families, were filed by 170 jurisdictions worldwide since 1940. A patent family is a collection of patent applications and granted patents covering similar technical content and linked by priority claims. In the present work we count one patent per family to represent the number of effective patent publications. Patents, like scientific publications, have surged over the last 14 years, with 75% published after 2010, totalling 2,873 publications. Most of these are inventions (69%), with utility models comprising 28.6% and designs only 2.4%. Notably, almost half (47%) of patent publications in solar desalination are inactive due to rejection, non-payment of annuities, or expiration of the protection term. Conversely, 33% of publications are still active, and 14% are pending

3.2.2 Countries of origin and classification

As shown in figure 6, 68.88% of patent publications originate from China, followed by India (6.84%) and the United States (4.17%). The remaining patents are distributed among 50 different countries. The International Patent Classification (IPC), created by the Strasbourg Agreement of 1971, and the Cooperative Patent Classification (CPC), jointly managed by the

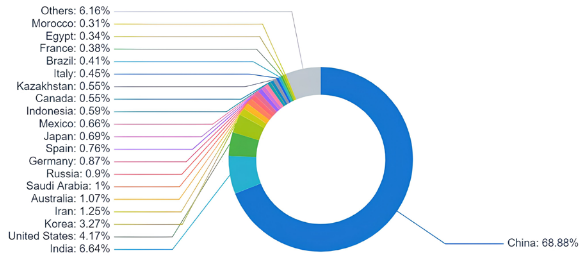

Figure 6. Top Countries of origin on solar desalination 2010-2023 PatSnap

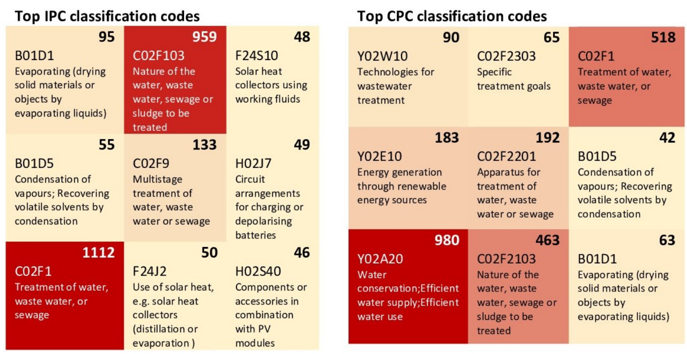

Figure 7. Top classification codes on solar desalination

European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO), are hierarchical systems for classifying patents by technological fields. The IPC comprises eight sections (A to H), subdivided into classes, subclasses, groups, and subgroups while CPC includes nine sections (A to H and Y). the section Y is dedicated to new technological developments and includes technologies that span multiple sections from various parts of the IPC. For the key technologies in solar desalination the distribution of patents according to the CPC and IPC classifications showed a concentration of publications in subclasses related to water treatment, particularly C02F1 and C02F103. Additionally, a significant portion of publications falls under the CPC-specific subclass Y02A20, which focuses on the supply, conservation, and efficient use of water (Figure 7).

4 Conclusion

The present study provides a comprehensive bibliometric analysis of scientific literature and patent on solar desalination, highlighting significant growth and trends in this critical field. Solar desalination, leveraging the planet's abundant solar energy and saltwater resources, offers a sustainable solution to the global water scarcity crisis, particularly in arid and sunny regions. Currently, desalination contributes only 1% of the world's potable water. This small contribution could be significantly enhanced if integrating the energy-intensive desalination process more frequently with renewable energies, particularly solar energy, as the most arid regions of the world are also the sunniest. The bibliometric analysis of scientific literature revealed a substantial increase in research output, with 6,927 publications indexed in Scopus up to 2023. The majority of these publications have emerged after 2010, indicating growing interest and investment in solar desalination research. India and China are leading contributors, with China also being the most academically influential in terms of citations (74,002), doubling the citations of India. The analysis underscores the importance of international collaboration, with an average collaboration rate of 28.4%. Furthermore, the literature is concentrated on six key subject areas, with notable growth in Energy and Materials Science (over 700%), indicating a rising interest in reducing energy consumption and exploring novel materials to improve the efficiency and performance of solar desalination processes. Additionally, keyword analysis indicated that the majority of publications on solar desalination primarily addressed thermal processes, while current industrial interest is shifting towards membrane processes. The patent analysis, conducted using the PATSNAP tool, identified 5,641 patents grouped into 3,854 families, filed by 170 jurisdictions worldwide since 1940. Similar to scientific publications, patents have surged over the last years, with 75% published post-2010. Most of these patents are inventions (69%), with utility models comprising 28.6% and designs only 2.4%. Notably, a significant portion of patents are inactive, highlighting challenges in sustaining patent protections. China leads in patent applications, followed by India and the United States, with a strong presence of academic institutions and research organizations. Patent classifications according to CPC and IPC show a concentration in subclasses related to water treatment, conservation, and efficient use of water. A key area for future research is the exploration of membrane processes, which are currently gaining traction in industry but remain underexplored in academic literature. Encouraging collaboration between researchers and industry stakeholders will be crucial in advancing these technologies. Policymakers should consider incentives for research and development in solar desalination and promote partnerships between public and private sectors to foster innovation and facilitate the adoption of these sustainable solutions. Technological innovations in solar desalination have seen significant advancements, such as the development of a plasmon-enhanced device using aluminum nanoparticles, which achieved a 90% efficiency improvement, as reported in a 2016 Nature Photonics publication [21]. Similarly, patent analysis reveals key breakthroughs, including one of the most cited patents focused on agile light control for solar desalination [22] and other fields, enhancing system efficiency and scalability. Additionally, the highest valued patent describes a multi-effect solar distillation system [23], which optimizes energy use and performance through innovative solar heat collection and vapor management components. These technological advancements not only push the boundaries of efficiency but also offer scalable, sustainable solutions to global water and energy challenges. Advancements in desalination technology have facilitated the increasing utilization of desalinated water as the principal source of municipal water supply across many regions. These innovations have markedly reduced unit costs, while current research endeavours aim to further diminish energy consumption and operational expenditures. The findings of this study provide valuable insights into the evolving landscape of solar desalination research and technology. This study serves as a resource for researchers and industry stakeholders, offering guidance for future research directions and strategies to address the global water scarcity challenge through sustainable desalination technologies.

The corresponding author for this work, Fatima BELMEHDI has a free access to the Scopus database, SciVal, and PatSnap Analytics through the National Center for Scientific and Technical Research.

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