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Boosting Desalination Efficiency: A 20-Year Global Bibliometric Analysis of Active Solar Stills Enhanced by Thermosolar Integration

Aumentar la eficiencia de la desalinización: Un análisis bibliométrico global de 20 años de alambiques solares activos mejorados mediante integración Termosolar

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Abstract

Solar stills represent an alternative for seawater desalination; however, their low production capacity poses significant limitations for broader applications. To address this, solar stills are increasingly integrated with Thermosolar systems to enhance performance and boost production capacity. This study undertakes a bibliometric analysis to evaluate the evolution of research on active solar stills integrated with Thermosolar systems over the period 2004- 2024. Using data from the Scopus database and VOSviewer software, this analysis explores key trends in publication

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output, co-occurrence of terms, leading authors, countries, continents, and universities. The findings highlight the most frequently studied types of active solar stills and their relationship with global solar radiation patterns. Additionally, the study assesses the contributions of various continents to this research domain, providing insights into the global landscape and identifying areas for future development.

Keywords: Active Solar Stills, Bibliometric Analysis, Desalination, Thermosolar Systems, VOSviewer

Resumen

Los destiladores solares representan una alternativa para la desalinización de agua de mar; sin embargo, su baja capacidad de producción plantea limitaciones significativas para aplicaciones más amplias. Para abordar esto, los destiladores solares se integran cada vez más con los sistemas termosolares para mejorar el rendimiento y aumentar la capacidad de producción. Este estudio realiza un análisis bibliométrico para evaluar la evolución de la investigación sobre destiladores solares activos integrados con sistemas termosolares durante el período 2004-2024. Utilizando datos de la base de datos Scopus y el software VOSviewer, este análisis explora las tendencias clave en la producción de publicaciones, la coocurrencia de términos, los autores principales, los países, los continentes y las universidades. Los hallazgos destacan los tipos de destiladores solares activos estudiados con más frecuencia y su relación con los patrones de radiación solar global. Además, el estudio evalúa las contribuciones de varios continentes a este dominio de investigación, brindando información sobre el panorama global e identificando áreas para el desarrollo futuro.

Palabras clave: Destiladores solares activos, Análisis bibliométricos, Desalinización, Sistemas Termosolares, VOSviewer

1. Introduction

Water, despite covering 71% of the Earth's surface, is a limited resource, as only 2.5% is fresh and most of it is frozen in Antarctica, leaving less than 1% available for human consumption [1]. The growing water crisis, exacerbated by climate change, has intensified drinking water scarcity in many regions [2]. Prolonged droughts and changes in precipitation patterns further complicate the situation, leading to the search for alternatives such as desalination to ensure future drinking water supplies [3].

Desalination can be classified into two types: active and passive [4]. Active desalination, which uses external energy [5], is efficient but costly due to its high energy consumption and the maintenance requirements of its mechanical components [6]. On the other hand, passive desalination, which does not require external energy or uses renewable sources such as solar energy [7], is cheaper but less efficient in terms of water production, limiting its use to small communities or areas with low demand [8].

Among the passive desalination methods, solar still stands out for its simplicity and low cost [9].

This system uses solar radiation to evaporate water and then collects the condensed vapor as distilled water, separated from the salts [10]. Although this technology is affordable and low maintenance, its production capacity is limited and ways to improve its efficiency are currently being investigated [11].

The use of solar energy in desalination offers several advantages. It is a clean and abundant source that reduces dependence on fossil fuels, and its design is simple and economical [12]. In addition, solar systems are especially efficient in areas with high solar radiation and require little maintenance, making them suitable for remote or resourcelimited areas [13].

However, there are disadvantages to the use of solar stills. Their efficiency depends directly on solar irradiation, which makes them less effective in areas with low sun exposure [14]. In addition, they require large surface areas to operate optimally, and their water production can be intermittent, especially on cloudy or rainy days. More advanced systems, such as solar stills with collectors, improve efficiency by capturing more solar energy, but this increases their complexity and cost [15]. Based on these considerations, a bibliometric analysis of passive solar stills is conducted to identify current trends in their research and application. The study is organized into four sections: the first presents the introduction, the second describes the methodology used, the third presents the results obtained, and the fourth discusses the main conclusions.

2. Methodology

This study used a four-stage bibliometric analysis to examine the evolution of research on active solar stills with solar thermal integration between 2004 and 2024. First, a search strategy was designed in the Scopus database with keywords such as “Solar Still” and “Solar Still

Desalination” to collect relevant publications. The data were downloaded on August 23, 2024, including information on authors, institutions, countries and journals.

The data were then processed with VOSviewer software to identify patterns of cooccurrence of terms and collaborative networks between authors and institutions. This analysis revealed the main trends in research, highlighting the most active countries and the most relevant technological configurations. Table 1 shows the search equations applied in Scopus, which refined the results from 2911 documents to 12 specific studies on solar stills with thermal collectors.

Table 1. Equations

<i>Item</i>	<i>Equation</i>	<i>Number of documents</i>
1	<i>Solar Still</i>	2911
2	<i>Solar Still AND Desalination</i>	1362
3	<i>Solar Still AND Solar Energy</i>	966
4	<i>Solar Still AND Integration</i>	99
5	<i>Solar Still AND Integration AND Desalination</i>	53
6	<i>Solar Still AND Solar energy AND Integration</i>	42
7	<i>Solar Still AND thermal collector</i>	12

3. Results and discussion

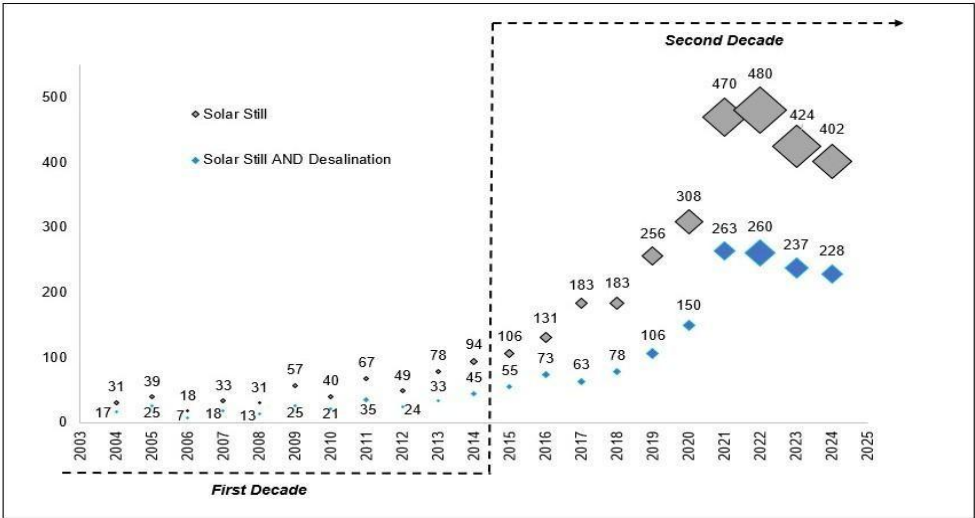
The term co-occurrence analysis based on Table 1 reveals a steady evolution in research on solar stills and desalination between 2004 and 2024. Key terms such as “Solar Still”, with 2911 papers, have dominated the research, reflecting a broad and sustained interest in solar stills.

“Desalination,” with 1362 papers, has also been a recurring theme, showing a strong relationship with solar, appearing in 966 papers. Emerging areas such as the integration of solar distillation systems with life cycle analysis (53 papers) and the combination of solar energy and integration (42 papers) have gained prominence in recent years, pointing to a trend towards optimizing the efficiency of these systems. Concepts such as “Thermal Collector”, with only 12 papers, indicate a more recent focus on improving heat capture to increase efficiency.

In the first decade, research on “Solar Still” averaged 38 papers per year, with a peak of 78 in 2013, while studies on “Solar Still AND Desalination” were even more limited. In contrast, the second decade showed exponential growth, peaking in 2022 with 480

publications on “Solar Still” and 263 papers in 2021 for “Solar Still AND Desalination”. This increase reflects the growing interest in the optimization of solar still distillation technologies, driven by the growing water crisis.

Figure 1. Number of publications with respect to years for equations 1 and 2.

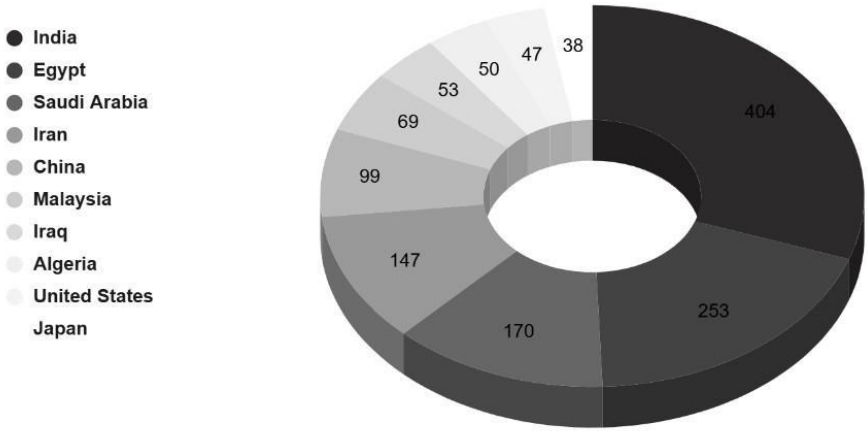


On the other hand, for the bibliometric analysis of publications on solar stills and desalination between 2004 and 2024 highlights a clear supremacy of Asia, which generates 73.8% of the research in this field. India is the leading country, with 404 papers, representing 30.4% of the total, followed by Iran, Saudi Arabia, China and other countries in the region, reflecting their focus on research into technologies to address water scarcity. This interest is particularly relevant in Asia, where water-related problems are increasingly critical due to growing demand and climate change.

Africa is the second continent in scientific production, with Egypt and Algeria as the main contributors, accumulating 24% of the publications. This highlights the importance of solar desalination in the region, where water scarcity is an urgent challenge. In contrast, North

America has a lower contribution, with the United States contributing 3.5% of the publications, suggesting a lower focus on this technology compared to Asia and Africa. Figure 2 evidence this regional leadership, with India and Egypt standing out in advancing research on solar stills.

Figure 2. Top 10 countries with the most publications on solar stills.



On the other hand, when comparing the publications data (see Figure 2) with the direct normal irradiance (DNI) levels measured in W/m^2 for the year 2023 from the Global Solar Atlas, it is observed that some countries with high solar irradiation, such as Australia and several North African countries, are not among those with the highest number of scientific publications in solar energy. Despite the fact that these regions have irradiation levels above $2500 \text{ kWh}/m^2$, their scientific output in this field is relatively low compared to countries such as India, Iran and China. This suggests that although solar irradiance is an important resource for the development of solar technologies, other factors such as research investments, academic infrastructure and local energy policies can significantly

influence the number of publications and scientific development. Therefore, although solar irradiance is a relevant indicator, it does not always translate directly into more research.

Figure 3 shows the top universities that have contributed to research on solar stills and desalination between 2004 and 2024, with Africa leading in publications. Tanta University tops the list with 162 papers, followed by Kafrelsheikh University with 104 publications. Other African institutions, such as Suez University and Delta University for Science and Technology, also contribute significantly. These universities play a key role in the development of solar desalination technologies, highlighting Africa's role as a continent committed to applied research to solve water scarcity.

In Asia, Prince Sattam Bin Abdulaziz University leads with 53 publications, followed by the KPR Institute of Engineering and Technology and Anna University, with 39 and 35 publications respectively. In addition, institutions such as the National Institute of Technology and B.S. Abdur Rahman University contribute outstanding research, reflecting Asia's growing interest in desalination technologies. This panorama coincides with the previously mentioned continents, where Africa and Asia are positioned as the main drivers of solar desalination research, reflecting the urgency of both regions to develop technological solutions to the water crisis.

Figure 3. *Top universities with the most publications on solar stills.*

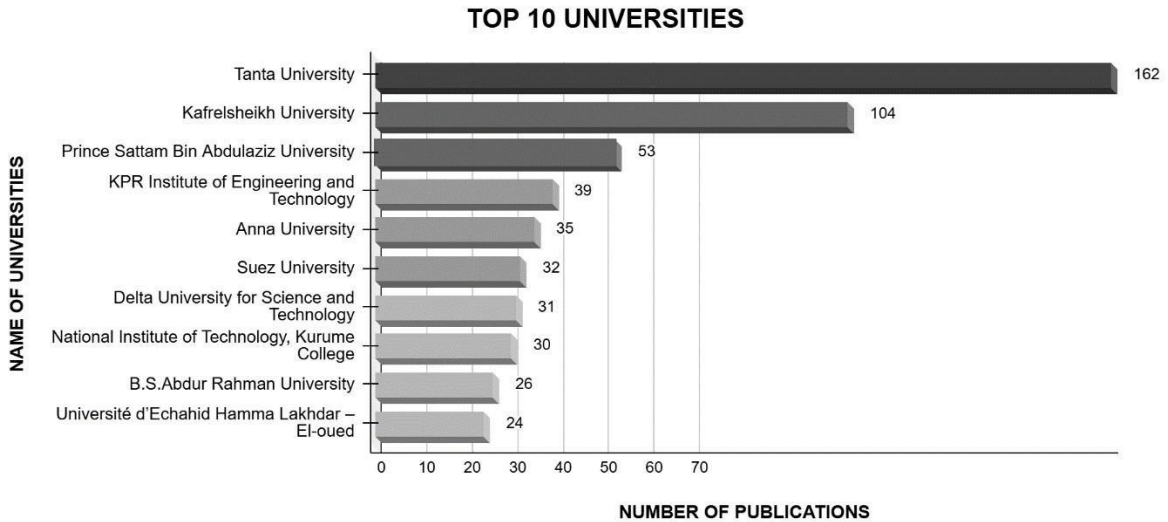
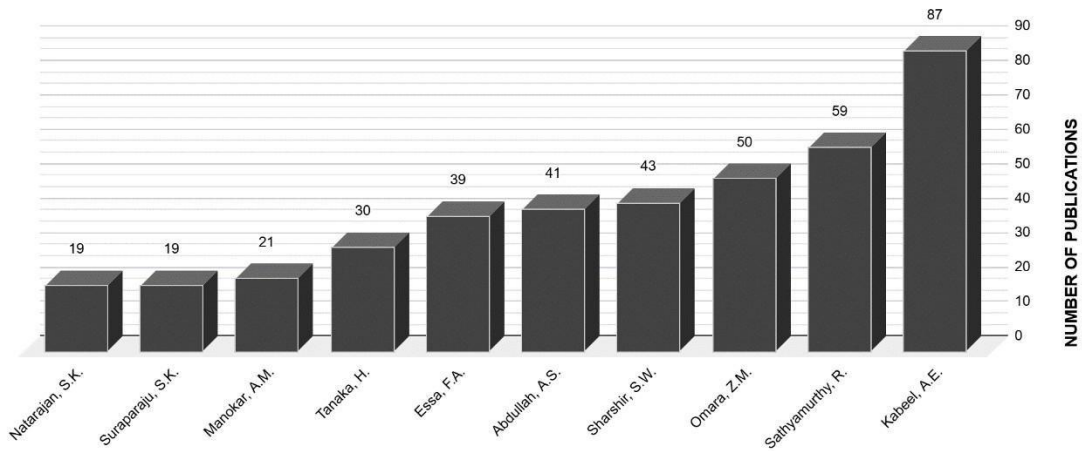


Figure 4 highlights the top 10 authors who have contributed to solar stills and desalination research between 2004 and 2024. A.E. Kabeel tops the list with 87 publications, evidencing his leadership in this field and his sustained focus on developing technological solutions for solar desalination. He is followed by R. Sathyamurthy, with 59 publications, consolidating his position as a key player in solar technologies research for water management. Z.M. Omara and S.W. Sharshir rank third and fourth with 50 and 43 publications, respectively, reflecting their impact on expanding knowledge in this area.

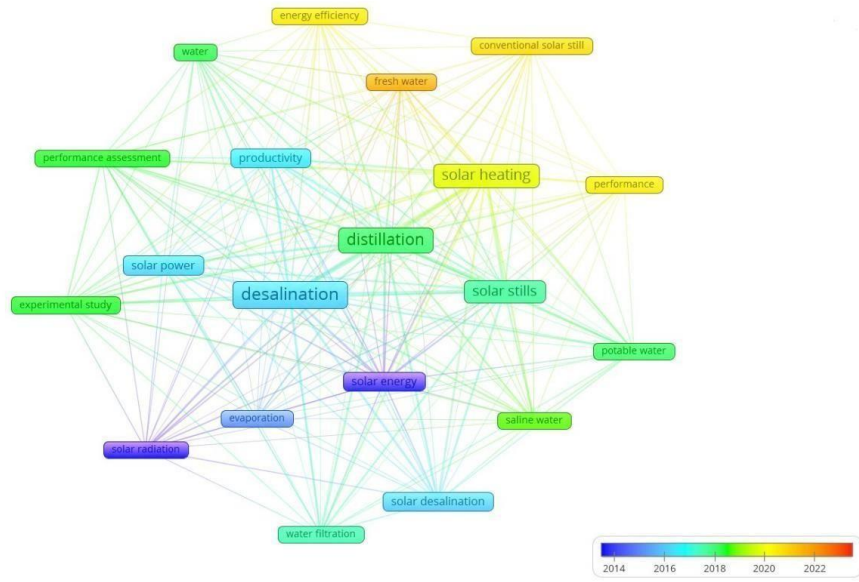
Figure 4. *Top 10 authors with more publications on solar stills.*



A.S. Abdullah, with 41 publications, and F.A. Essa, with 39, also stand out for their significant contributions to the development of solar desalination technologies. H. Tanaka, with 30 publications, reinforces his position as one of the leading researchers in Asia. Other authors, such as A.M. Manokar, S.K. Suraparaju and S.K. Natarajan, complete the top 10, demonstrating a growing interest and commitment to solar still research, underlining the importance of this field in the search for sustainable solutions to water scarcity.

The co-occurrence analysis of terms is presented in Figure 5 and shows that research on solar stills and desalination has focused primarily on the integration of solar technologies to produce drinking water from saline water. Key terms such as desalination and distillation are the most connected concepts, reflecting the sustained interest in these technologies. Initial studies between 2014 and 2016 focused on solar radiation and solar energy, while in more recent years topics such as energy efficiency and solar heating have gained prominence, indicating a growing interest in optimizing the performance of these systems.

Figure 5. Cooccurrence of terms



In recent years (2020-2024), research has moved towards improving conventional solar stills, with a particular focus on integration with active solar thermal technologies, which has partly displaced interest in passive systems. Although passive solar stills continue to be a viable option, recent studies highlight more efforts to optimize active systems to improve energy efficiency and drinking water production. This reflects a trend towards implementing more complex and sustainable technological solutions to address the global water crisis.

On the other hand, the table shows the studies of the last decade that focus on the integration of solar stills with solar collector systems. Research on solar desalination has shown a trend towards the integration of solar collectors, mainly flat plate and evacuated tube collectors. However, solar concentrators, such as parabolic and Fresnel concentrators, have seen more frequent use in recent years, especially in studies focused on improving the performance of solar stills through hybrid technologies or integrated

systems with energy storage, such as phase change materials (PCMs). Solar collector systems predominate in experimental studies, while solar concentrators are more common in research combining experimentation with simulation.

In terms of research methodologies, the experimental approach remains the dominant one, reflecting a growing interest in testing and optimizing technologies under real conditions to improve the efficiency of solar stills. Simulations, although less frequent, are mainly used to analyze and compare different designs prior to their experimental validation. Recent trends show an increase in the use of hybrid technologies, such as the integration of solar collectors with phase change materials (PCM) and nanofluids, with the aim of improving energy storage and transfer. The year 2023 and 2022 are the periods with the highest research activity, according to the table, with notable growth in innovative approaches such as parabolic tube collectors and advanced concentrating solar systems. This reflects a growing interest in improving the efficiency and feasibility of solar desalination in various regions of the world.

Table 2. *Recent Studies on the Integration of Solar Stills with Solar Collectors (2014-2024)*

Author (APA)	Year	Purpose	Article Type	Study Type	Technology
[16]	2024	Explore a cylindrical solar still integrated with various technologies.	Article	Experimental	Cylindrical solar still with parabolic concentrators
[17]	2024	Examine large scale applications of solar desalination using evacuated glass tube collectors.	Review	Review	Evacuated glass tube collectors in desalination
[18]	2024	Evaluate the integration of solar collectors with conventional solar stills.	Article	Experimental	Solar collectors with conventional stills
[19]	2024	Review advances in solar still technology for desalination.	Review	Review	Solar stills

[20]	2024	Review advanced desalination technologies for all-day, allweather freshwater systems.	Review	Review	Advanced desalination technologies
[21]	2023	Analyze the performance of a single slope solar still with solar dish concentrator.	Article	Experimental	Single slope solar still with dish concentrator
[22]	2023	Improve fresh water production using magnetic flux, solar collector, and phase change materials.	Conference Paper	Experimental	Solar distillation with magnetic flux and phase change materials
[23]	2023	Enhance the performance of solar distiller with phase change material and parabolic trough collector.	Article	Experimental	Solar distiller with phase change material and trough collector
[24]	2023	Understand and compare different designs of solar still.	Conference Paper	Theoretical	Various solar still designs
[25]	2023	Evaluate the use of evacuated tubes, perforated fins, and pebbles in solar stills.	Article	Experimental	Evacuated tubes, perforated fins, and pebbles in solar stills
[26]	2022	Enhance productivity of drum solar still using parabolic solar concentrators and nanoparticles.	Article	Experimental	Drum solar still with parabolic concentrator and nanoparticles
[27]	2022	Analyze thermal performance of solar still using silver nanofluids in direct absorption.	Article	Experimental	Silver nanofluids in solar stills

[28]	2022	Improve performance of hybrid solar desalination system under various conditions.	Article	Experimental	Hybrid solar desalination
[29]	2022	Evaluate self-powered solar desalination using solar still with PCM and external solar collector.	Article	Experimental	Solar still with PCM and external solar collector
[30]	2022	Enhance solar desalination with evacuated tube heat pipe and wind ventilator condenser.	Article	Experimental	Evacuated tube heat pipe and external condenser in solar desalination
[31]	2022	Improve thermal efficiency and water yield of tubular solar still with neural network optimization.	Article	Experimental	Tubular solar still with neural network optimization
[32]	2022	Study phase change materials integrated in solar still with solar collector.	Article	Experimental	Phase change materials in solar stills
[33]	2022	Evaluate a V-type solar still integrated with hybrid solar concentrator and heat exchanger.	Article	Experimental	V-type solar still with hybrid solar concentrator

[34]	2021	Explore sea-water desalination using a parabolic trough collector and activated carbon.	Article	Experimental	Sea-water desalination with parabolic trough and activated carbon
[35]	2021	Enhance solar desalination efficiency with parabolic trough collector.	Article	Experimental	Parabolic trough collector in solar desalination
[36]	2021	Techno-economic study of a new hybrid solar desalination system for fresh water in hot-arid climates.	Article	Experimental	Hybrid solar desalination system
[37]	2021	Review of evacuated tube solar collector for desalination.	Article	Review	Evacuated tube solar collector
[38]	2021	Evaluation of solar still productivity in different climates.	Article	Experimental	Flat plate and parabolic trough collectors
[39]	2021	Review of nanomaterials' impact on solar distillation systems.	Review	Review	Nanomaterials in solar stills
[40]	2021	Performance enhancement of tubular solar still using PCM-tubes.	Article	Experimental	PCM-tubes in solar stills
[41]	2021	Evaluate performance of pyramidshaped solar still with flat plate collector.	Article	Experimental	Pyramid-shaped solar still with flat plate collector
[42]	2021	Investigate a solar desalination system coupled with solar collector and packed bed.	Article	Experimental	Solar desalination with solar collector and packed bed
[43]	2020	Analyze solar desalination under concentrated solar flux and reduced pressure.	Article	Experimental	Solar desalination under concentrated solar flux and reduced pressure

[44]	2020	Examine performance of a threeeffect tubular solar desalination system with vacuum operation.	Article	Experimental	Three-effect tubular solar desalination system
[45]	2019	Analyze performance of a solar desalination system with concentrated solar power (CSP).	Conference Paper	Experimental	Solar desalination with concentrated solar power (CSP)
[46]	2018	Theoretical investigation of solar desalination with phase change material and solar collector.	Article	Theoretical	Solar still with phase change material and solar collector
[47]	2018	Development and performance evaluation of an active solar distillation system with vacuumtype heat exchanger.	Article	Experimental	Active solar distillation system with vacuum-type heat exchanger

[48]	2018	<i>Solar desalination using solar still enhanced by external solar collector and PCM.</i>	<i>Article</i>	<i>Experimental</i>	<i>Solar still enhanced by external solar collector and PCM</i>
[49]	2017	<i>Review of hybrid solar desalination and water heating systems.</i>	<i>Review</i>	<i>Review</i>	<i>Hybrid solar desalination and water heating system</i>
[50]	2017	<i>Investigate exergy and yield of a passive solar water desalination system with parabolic concentrator and latent heat storage.</i>	<i>Article</i>	<i>Experimental</i>	<i>Passive solar desalination system with parabolic concentrator and latent heat storage</i>
[51]	2016	<i>Analyze performance of a desalination unit coupled with a solar water lens concentrator.</i>	<i>Conference Paper</i>	<i>Experimental</i>	<i>Solar desalination unit with water lens concentrator</i>
[52]	2016	<i>Evaluate performance of a triple basin solar desalination system with cover cooling and parabolic dish concentrator.</i>	<i>Article</i>	<i>Experimental</i>	<i>Triple basin solar desalination system with cover cooling and parabolic dish</i>
[53]	2016	<i>Examine seasonal behavior and techno-economic analysis of a multi-stage solar still with Fresnel lens.</i>	<i>Article</i>	<i>Theoretical</i>	<i>Multi-stage solar still with point-focus Fresnel lens</i>
[54]	2015	<i>Improving double slope solar still performance using flat-plate solar collector and cooling glass cover.</i>	<i>Article</i>	<i>Experimental</i>	<i>Double slope solar still with flat-plate collector</i>
[55]	2015	<i>Single slope solar water still with enhanced solar heating system.</i>	<i>Book Chapter</i>	<i>Experimental</i>	<i>Single slope solar still with solar preheating</i>
[56]	2015	<i>Spiral multiple-effect diffusion solar still coupled with vacuum-tube collector and heat pipe.</i>	<i>Article</i>	<i>Experimental</i>	<i>Spiral multiple-effect diffusion solar still</i>
[57]	2014	<i>Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe.</i>	<i>Article</i>	<i>Experimental</i>	<i>Multiple-effect diffusion solar still with vacuum-tube collector</i>

4. Conclusions

Most of the research on solar stills has been experimental in nature, focusing on the practical validation and optimization of these technologies under real conditions. This reflects the importance of testing the efficiency and viability of solar systems in different

environments, prioritizing the implementation of applied solutions over the exclusive use of theoretical simulations.

While countries with high solar irradiance, such as India and Iran, lead in research on solar technologies, some regions with high irradiance, such as Australia and North Africa, do not have a proportionally high scientific output. This suggests that, in addition to irradiance, factors such as research investments, academic infrastructure and local energy policies are crucial in driving scientific output.

In recent years, there has been a significant increase in the development of solar desalination systems that integrate hybrid technologies, such as solar collectors and phase change materials (PCMs). This trend reflects a growing focus on improving energy efficiency and water production capacity, highlighting the importance of technological innovation in the search for more sustainable and efficient solutions to the global water crisis.

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