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# A semi-systematic review and bibliometric analysis of life cycle assessment in solar desalination technologies (2004–2024)

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**Abstract**

Water harvesting for human consumption faces growing challenges due to extreme climatic events, leading to the exploration of alternative sources such as groundwater and seawater. Desalination has become a viable solution despite technical and environmental limitations. Life Cycle Analysis (LCA) is widely used to assess the environmental impacts of desalination technologies, positioning solar desalination as a promising option for coastal areas. However, differences in LCA methodologies limit the identification of consistent trends. This study presents a bibliometric analysis using VOSviewer and the SCOPUS database to update the state of the art in LCA applications for desalination systems, with emphasis on solar desalination. A total of 165 documents published between 2004 and 2024 were analyzed in two periods. A significant increase in publications was observed from 2015, particularly in Asia and the Arabian Peninsula, aligning with high solar potential and financial capability. From the 29 selected papers, 12 were directly related to LCA methodologies, covering scope, typologies, impact categories, and tools. Although no single method dominates, ReCiPe has gained attention, while IMPACT 2002+ and IPCC-2013 remain in use. Commonly assessed impact categories include Global Warming Potential (GWP100a), Acidification Potential (AP), and Eutrophication Potential (EP).



*Keywords*: Desalination, Environmental impacts, Life cycle analysis, VOSviewer

## 1. Introduction

The "Water and Energy Declaration" pointed out desalination technologies of salt water sources as crucial solutions for water security, but also as a relevant hotspot of the water-energy-climate nexus because of their high operational energy requirements [1]. Subsequently, in 2010 the United Nations (UN) General Assembly adopted a resolution recognizing access to safe drinking water and sanitation services as a human right and later, both issues were incorporated as essential part of the sustainable development goals; particularly, the Sustainable Development Goal (SDG) No. 6, based on "Clean Water and Sanitation", which aims an equitable and universal access to safe drinking water [2], despite the most recent UN Water Development Report announces that more than 2 billion people do not have access to these services [3]. Nevertheless, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the World Health Organization (WHO) claim water to be the most precious resource for life and progress, calling it the "Blue Gold" [4].

Stress and overexploitation of freshwater sources threatens the reliable and stable supply of drinking water worldwide, particularly in low-income regions, because clean surface waterbodies are scarce and unevenly distributed on earth, leading to important infrastructure investments and operational costs, such as building of dams and reservoirs for storage, and installation of water distribution networks, including their pumping systems to extract water and transport it to where it is consumed, also involving significant energy consumption for collection and treatment to drinking standards [5] [6].

For several years now, the production of clean water from seawater, the most abundant water resource, is a viable alternative and it must be the natural choice for supplying half of the global population being settled in coastal areas; paradoxically, desalination provides only around 1% of the world's drinking water and although this figure is expected to be doubled by 2030, the massive utilization of saline water remains as a pending checkmark for the drinking water sector worldwide [7]. Indeed, desalination includes a wide and diverse variety of technologies to remove salts from seawater and brackish water; filtration, osmotic membranes, thermal processes, and hybrid systems are the most commonly used to tackle the problem of freshwater shortages and the rising water demand in various regions worldwide. However, the cost-effectiveness of these processes must be improved by decreasing even further the current capital and operational costs. The latter is mainly represented by electricity and thermal consumption (20% – 35%) due to operation requirements and saltwater pumping, as well as associated costs to chemicals, maintenance, and disposal of brines, which are generated as the main by-product in membrane-based technologies (15% – 30%) [8] [9].

The simplest way to classify desalination technologies is to group them as direct and indirect, from the perspective of their modularity. While direct systems consist of a single unit where the full process is carried out, commonly known as "solar stills" [10]; the indirect ones require an adaptation to the desalination system, based on the supply of electrical or thermal energy depending on the process, it means, that the system consists of two or more subsystems or parts [9] [11]. In turn, indirect technologies are classified into two groups, evaporative phase-change-based and membrane processes, as shown by Figure 1, where white boxes identify commercially or mature technologies and red boxes point out those considered emerging or under development.

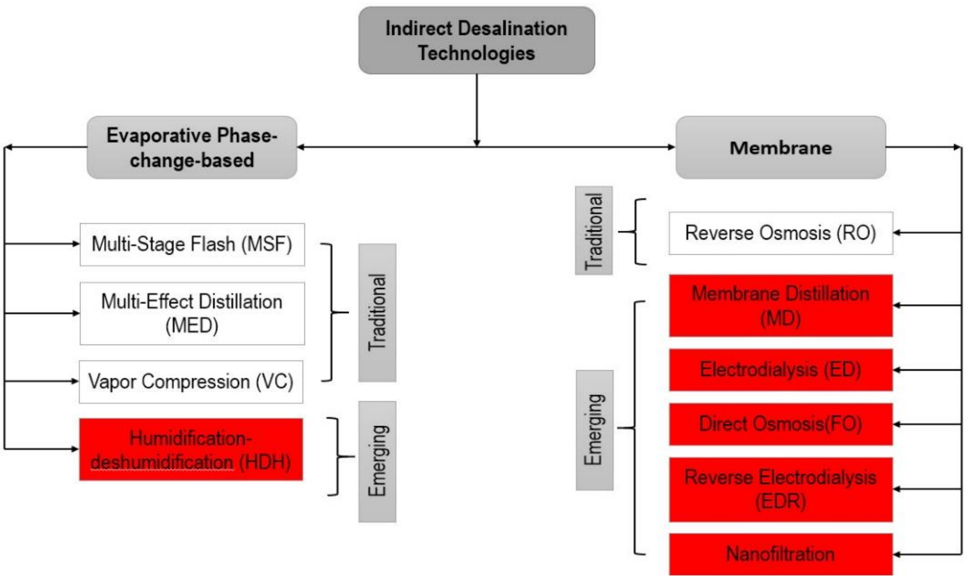


Figure 1. Classification of the main indirect desalination technologies (based on: [8] [9] [11])

Continuous improvements in the equipment used by these technologies during the last two decades are gradually positioning desalination as an economic and viable option for clean water supply, but salt concentration still determines the major operational costs and the application domains of each desalination technology. To illustrate this observation, Figure 2 relates typical energy consumption ranges of the main indirect desalination technologies against the concentration of total dissolved solids (TDS) in the feedstock water, which is a parameter directly related to the salinity. It can be observed that evaporative phase-change-based technologies are adequate for handling higher TDS levels, requiring faster concentration rates and consequently, more energy consumption. In other words, there is a direct relationship between the solids concentration rate and the energy consumption to carry out the desalination process. On the other hand, the membrane group technologies is more adapted to TDS in the order of 0 to 60000 mg/L and have a lower energy consumption range than thermal technologies, by around 2 to 9 kWh/$m^3$ of treated water, that continues being high for medium or low scale applications. This explains the research effort for new solutions by improving the membrane-based technologies or seeking alternative principles of separation to the reverse osmosis (RO), the "standard-gold" to produce drinking water from sea and brackish waters [9] [12].

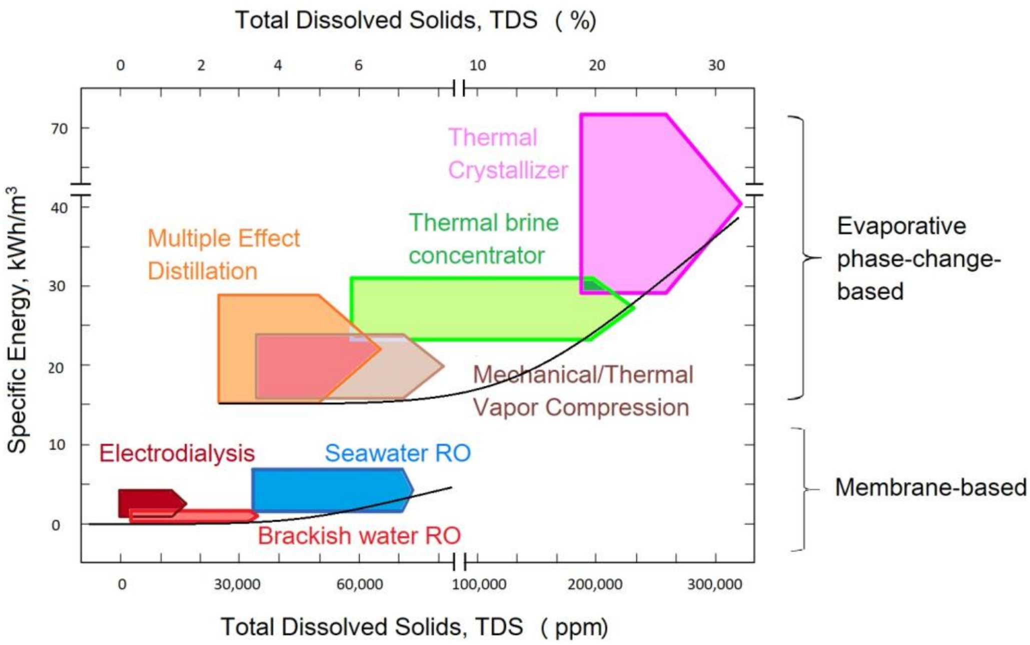


Figure 2. Desalination technologies applied to water treatment and their energy consumption (Adapted from Tow et al. 2015, and the keynote by Anderson, M., during the 2nd Water-Energy Nexus Conference, November 2018, Salerno, Italy)

Beyond energy efficiency and economic topics, desalination technologies must be analysed from an environmental perspective, especially considering those indicators that also influence their sustainability, competitiveness, and range of application. Although desalination projects themselves address environmental concerns, offering a way to face quality deterioration of freshwater sources, drought, and drinking water access to coastal settlements, their implementation is limited by other environmental aspects particularly stressed during their construction and operation stages, criticizing their environmental compatibility and even their sustainability in a broader sense [12] [13]. In general, adverse impacts due to the operation of mature RO and thermal desalination processes depend on the proper handling of the co-produced brine and carbon emissions associated with their elevated energy demand. The brine being a reject that usually is discharged back to the marine environment despite their huge salinity and chemicals concentration and the carbon footprint of desalination plants clearly linked to the salt concentration of the raw inlet effluent and the operation purpose, thus, desalination systems for water reuse entails lower CO2 emissions than seawater RO [13] [14] [15].

Life Cycle Assessment (LCA), the methodology most extended to evaluate the environmental impacts of all kinds of products and processes along their supply-chain [16] [17], has been also applied to study the environmental impact of installed and pilot desalination facilities for different types of salty waters, in order to develop strategies for reducing their potential adverse impacts even from early development stages. Since pioneering applications of LCA for desalination systems by 2004, the integration of the energy production systems, particularly provided by a significant contribution of renewable sources, has been the way to these technologies, provoking a lower environmental footprint [18]. However, it took nearly 10 years for the application of LCA to these systems to be reviewed in essential methodological aspects, such as approaches in the selection of impact assessment methods, the availability, representativeness, and uncertainty of information in environmental databases, and criteria to outline the system boundaries, among others [19]. At the same time, like many other applications of LCA, preferably evolved towards the exclusive evaluation of the carbon footprint with their methodological particularities [20]. Likewise, energy-efficient desalination technologies and their degree of "greener" were analyzed for centralized and decentralized systems, finding differentiated opportunities for renewables in urban and rural areas [21]. Since the middle of the last decade, a rapid outlook of the LCA of desalination systems, seems to point out that brine management captures more and more attention [22], as well the first attempts to realize a comprehensive assessment of sustainability of desalination technologies by integrating LCA with complementary approaches, which may include economic and social aspects [23] [24].

Consequently, this study proposes a bibliometric analysis to identify recent publications on the approaches used to apply the LCA method to desalination processes and explore in more detail how LCA evolves in its application in this field, the methodological options most used by practitioners, and what major contributions of the LCA methodology are to improve the environmental performance of desalination systems. Bibliometric analysis is a method oriented to examine large volumes of information of scientific publications and their citation patterns, allowing for understanding the dynamics of change in a research field, recognizing trends, methods, new topics, advances, and knowledge gaps within it. In summary, bibliometrics is a valuable tool that facilitates the processes of exhaustive and rigorous review of scientific Information, being particularly useful for updating the state of the art, which at the current pace of research changes more dramatically over shorter periods of time. Bibliometric analysis makes use of specialized software that generates bibliometric networks and identifies key relationships between authors, journals, institutions, and thematic communities of science, by means of graphic tools and maps. Some examples of this type of informatics tools are open access, for instance, Cite Space, VOSviewer, and Bibliometrix.

To further explore the topic, the objectives of this review focus on a comprehensive understanding of the status of the application of the life cycle analysis (LCA) approach to solar desalination systems. To this end, the evolution of research over the last two decades is analyzed to identify the dynamics of this field during this period. Initially, an exploratory phase was carried out to identify the main countries that have disseminated documents on the LCA approach in desalination and solar desalination systems, grouping them by continent. This process made it possible to establish the relationship of each country with indicators of solar resources, access to water, and gross domestic product (GDP). Subsequently, a detailed evaluation of documents dealing exclusively with the LCA approach and solar desalination was carried out, identifying methods, programs, study types, and impact categories most commonly applied in the literature. In summary, through a bibliometric analysis, this study will provide valuable information about the LCA approaches and their current practices in the field of solar desalination technologies.

In this view, the article is organized as follows: Section 2 presents the methodological aspects, defining the information search equations, as well as presenting the scope and limitations of the bibliometric study. Section 3 covers a bibliometric analysis of solar desalination systems, taking desalination technologies as a starting point and then filtering the information to those technologies that link solar energy in their process. The bibliometric analysis is linked to the VOSviewer software and focuses on the incidence of countries, authors, main sources, and institutions in the publication of documents on the research topic, as well as their citation indexes, to finally define the main typologies and specific methodological characteristics of LCA applications to solar desalination in the last 10 years. Finally, some conclusions are summarized in Section 4.

## 2. Methodology

The bibliometric analysis aims to carry out an exploratory assessment of the period from 2004 to 2024 on LCA in solar desalination systems using the SCOPUS database. The purpose is to examine the evolution in the application of this type of assessment from the first decade to the second decade. Table 1 presents the four search equations, as well as the keywords and terms used for the document filtering process in Scopus. The search process was performed on May 06, 2024.

Table 1. Categories of document search in the research period 2004 to 2024

| Scenary | Search Within | Search string | Number of Documents |
|---|---|---|---|
| 1 | All Fields | TÍTULO-ABS-CLAVE (life* cycle* analysis*) AND (“Desalination”) | 2872 |
| 2 | All Fields | TÍTULO-ABS-CLAVE (life* cycle* analysis*) AND (“Desalination”) AND (“Solar”) | 1352 |
| 3 | Article, Abstract, Keywords | TÍTULO-ABS-CLAVE (life* cycle* analysis*) AND (“Desalination”) | 165 |
| 4 | Article, Abstract, Keywords | TÍTULO-ABS-CLAVE (life* cycle* analysis*) AND (“Desalination”) AND (“Solar”) | 40 |

The search methodology employed has the following limitations:

i. The SCOPUS database that was used, when compared with WOS, may yield similar results; however, there may be a minimal variation in the number of total documents.
ii. Only articles written in English were included, excluding some potential papers presented in other languages.
iii. Keywords used are relevant to the topic of study; the use of other terms could generate a broader and/or more specific analysis that was not considered.

## 3. Results and analysis

### 3.1. Exploratory evaluation

A total of 165 documents were evaluated using the search string 3, as described in Table 1, excluding the term "solar". Subsequently, by refining the search with 4, we were able to identify 40 documents that specifically address the topic of solar desalination. As for the trend in the publication of these documents over time, it is presented in Figure 3, where a grouping into two decades is observed: the first, comprised between 2004 and 2014, and the second, from 2015 to 2024.

The analysis reveals a significant increase in the publication of documents between the first and second decades. Specifically, a 1.9-fold increase is observed for those papers that focus on life cycle analysis and desalination. However, when considering the use of solar energy in desalination processes, this increase becomes even more remarkable, reaching a multiplication of 2.5 times increase in documents in the second decade.

Overall, the average number of publications per year of the 164 papers initially evaluated is 7.80. This average is 5.95 per year when filtering out publications that do not include solar energy, and 1.85 per year when specifically considering solar energy use. Based on these data, one can observe a steadily growing interest in the last 5 years in life cycle analysis applied to desalination and solar desalination systems. This is reflected in an average of 10 and 4.2 papers per year, respectively, specifically for the period from 2020 to 2024.

Among the studies analyzed, the most cited article on the topic of Life Cycle Assessment (LCA) applied to solar desalination stands out: Jijakli et al. titled *"How green solar desalination really is? Environmental assessment using life-cycle analysis (LCA) approach,"* published in the journal *Desalination*. This pioneering study has been widely referenced due to its innovative approach in evaluating the environmental performance of solar-driven desalination systems using LCA as a methodological tool. Its high citation count highlights its significance as a key reference in the intersection of sustainability and solar desalination technologies.

In addition, two review papers presented in the second decade were identified during the exploratory phase, both of which deal directly with the application of Life Cycle Assessment (LCA) to desalination systems, excluding the focus on solar energy. Lee & Jepson reviewed 38 studies with 295 LCA scenarios on desalination for a research period between 2000 and 2018. The authors presented an evidence map that allows them to identify key points such as energy, chemical, and material consumption in the desalination process, which contribute negatively to environmental impacts. In addition, they mention emerging desalination technologies, such as low-energy intensity, with high potential to reduce environmental impacts. In turn, Aziz & Hanafiah evaluated 64 studies for a research period between 2004 and 2019. The authors highlight that the environmental studies of desalination processes are concentrated in the areas of energy consumption and brine generation. In addition, they mention that the integration of renewable energies with conventional desalination technologies generates sustainable systems with lower environmental impact.

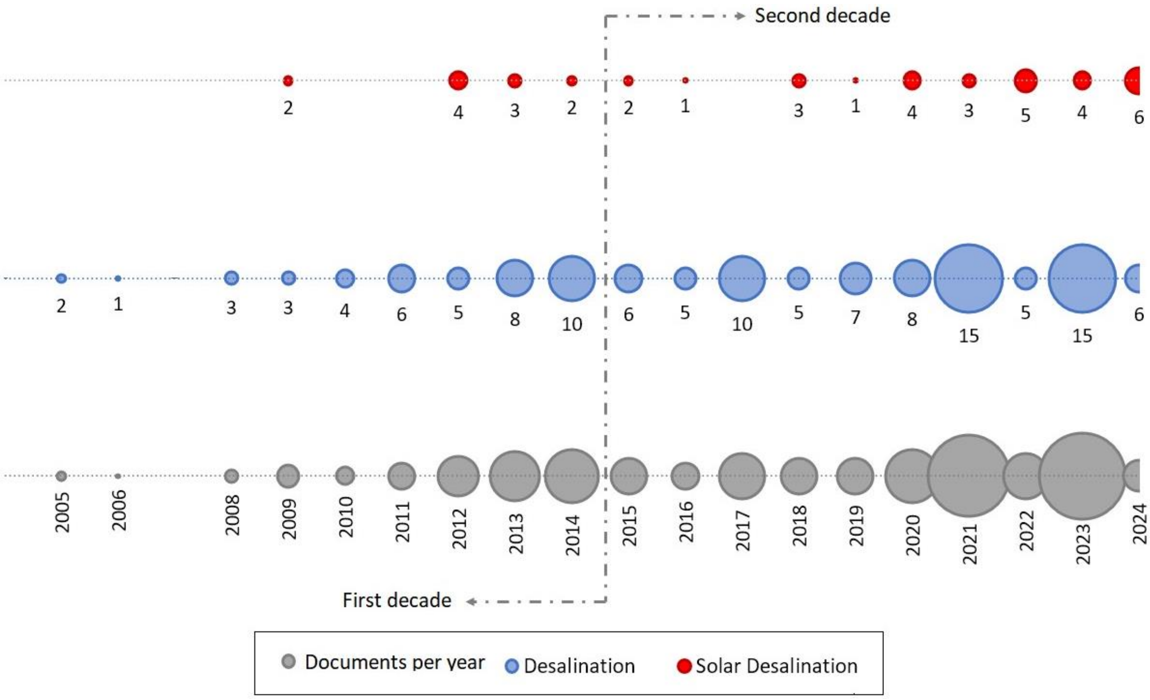


Figure 3. Timeline of documents published in the period 2004 to 2024 for life cycle analysis in desalination and solar desalination. The ratio of the size of the circle is directly proportional to the number of documents published.

Then, an analysis of the participation of each country in the publication of desalination and solar desalination documents during the period 2015-2024 was performed, classifying them by continent. Asia leads with 47.62% of the documents published, as shown in 4A, followed by Europe (22.62%), North America (12.5%), Oceania (10.12%), Africa (5.36%), South America (1.19%), and Central America (0.6%). As expected, the countries with the highest number of publications are located in the three continents with the highest percentage of participation; China is the leader with 20 papers (Asia), followed by the United States with 19 papers (North America) and Australia with 17 papers (Oceania). Subsequently, the participation of each continent is evaluated, identifying publications related to desalination and solar desalination, as shown in Figure 4 B. In percentage terms, Central America leads the number of publications on desalination, followed by Asia and Europe (both with 34%), Africa (33%), North America (14%), Oceania (6%), and South America (0%). However, when comparing the percentage of published papers by continent focused on solar desalination, Asia stands out as the continent with the highest number of publications, being 2.07 times higher than Europe, which is next on the list.

The coexistence of solar radiation, access to potable water, and gross domestic product (GDP) underscores the importance of assessing the interest of countries in developing life cycle analyses for desalination and solar desalination processes worldwide. Solar radiation is an essential resource for the efficiency of these processes, while access to clean water and economic status (GDP) are critical indicators of a country's development and investment capacity. Identifying the countries that exhibit correlations between these aspects and the topic under study allows a better understanding of their interest, as they recognize the environmental, economic, and social impacts of these technologies. This positions them as key players in making informed decisions and addressing the drinking water needs and sustainable development in their respective regions.

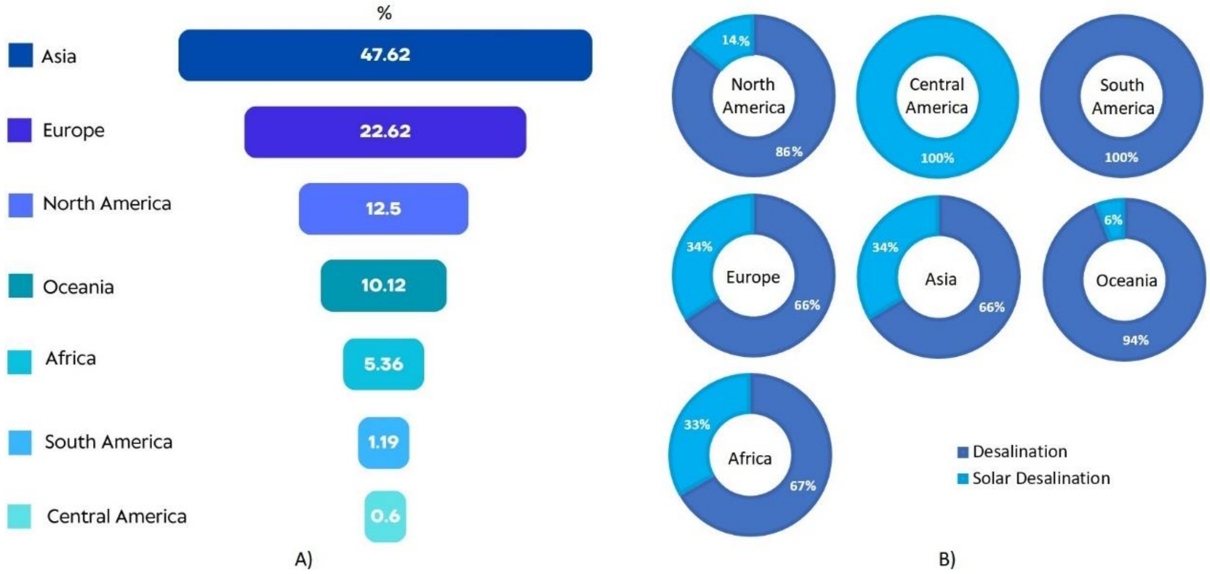


Figure 4. Participation in Scopus publication of papers (2015-2024): A) Total contribution (%) of desalination papers by continent; B) Total desalination vs. solar desalination (%) papers by continent

Figure 5 correlates the 2023 solar resource map, published by the World Bank Group and prepared by Solargis with ESMAP funding, with the total percentage of life cycle analysis (LCA) documents on desalination and solar desalination analyzed in this study during the period 2015-2024 for each continent. In addition, it shows the percentage of published documents directly referring to desalination and solar desalination, respectively, for each continent.

From the above, the interpretation of Figure 5 is simple, as it seeks to discern the general interest of each continent and its countries in addressing the topic of Life Cycle Assessment applied to desalination and solar desalination, taking into account the availability of the solar resource. The most relevant observations are presented below.

- In Asia, the East, West and South regions are distinguished by high levels of solar radiation throughout the year, and are home to the Asian countries most interested in Life Cycle Assessment (LCA) studies applied to desalination and solar desalination, such as China (East Asia), Saudi Arabia, Qatar, United Arab Emirates (West Asia), India and Iran (South Asia). In contrast, North Asia, which consists of only one country, experiences lower levels of solar radiation throughout the year and lacks publications on this topic of study.
- In Europe, the southern region stands out for its higher levels of solar radiation compared to the eastern, western, and northern regions. As expected, Spain, located in this region, shows the greatest interest in

LCA studies applied to desalination and desalination within the European continent. However, unlike in Asia, in Europe, some countries located in areas with lower radiation levels, such as Germany, France, and the Netherlands in the west, as well as England in the northwest, also show interest in this topic.

- In North America, Mexico and the United States stand out for their high levels of solar radiation compared to Canada; however, Mexico lacks publications on LCA studies applied to desalination and solar desalination. As expected, the United States, with its high levels of radiation, shows the greatest interest in the topic of study, in contrast to Canada, which shows a minimal number of publications on this topic.
- Oceania and Africa are two continents that enjoy high levels of solar radiation throughout their territories. Australia, in the case of Oceania, stands out as the country with the highest level of radiation, being the only one showing interest in LCA studies applied to desalination and desalination. In Africa, the trend is similar: Egypt, Morocco, Tunisia, and South Africa are countries with the highest radiation levels on the continent and are the only ones to express interest in this subject of study.
- In Central and South America, radiation levels throughout their territory are varied and show the least interest in the topic of study, suggesting that the correlation between radiation and interest in the topic in these continents does not have a great impact on the study.

In general, there is a significant correlation between solar radiation levels and interest in Life Cycle Assessment (LCA) studies applied to desalination and solar desalination in various regions of the world. In Asia, Europe, North America, Oceania, and Africa, countries with higher radiation levels show greater interest in this topic, while those with lower levels show less interest. However, this correlation does not hold consistently in Central and South America, where radiation levels vary but interest in the topic is lower overall. This suggests that other factors may influence interest in these studies in these regions. In summary, although solar radiation appears to influence interest in these studies in many parts of the world, it is not the sole determining factor, and each region may have its own motivations and priorities regarding desalination and solar desalination.

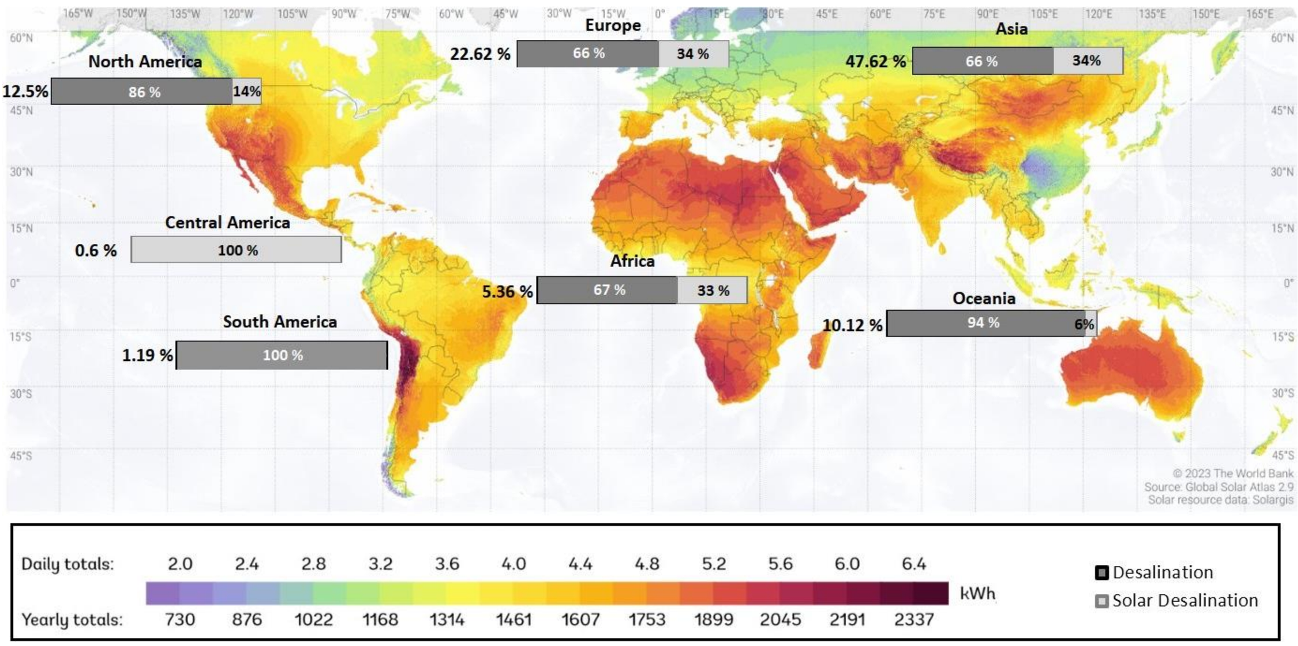


Figure 5. Correlation of the 2023 solar resource map, published by the World Bank Group and prepared by Solargis with ESMAP funding, with the total percentage of LCA documents on desalination and solar desalination analyzed in this study during the period 2015-2024

Alternatively, Figure 6 correlates the map of the number of people without access to safe drinking water by 2020, jointly presented by the World Health Organization (WHO) and the United Nations Children's Fund

(UNICEF), with the total percentage of Life Cycle Assessment (LCA) papers on desalination and solar desalination analyzed in this study during the period 2015-2024 for each continent. However, the lack of data in the map for countries with a prominent participation in the publication of documents on the topic under study, such as China, Saudi Arabia, Qatar, United Arab Emirates Australia, Panama, Egypt, Tunisia and South Africa, restricts the correlation process with the continents: Asian, Oceanic, Central American and African.

In Europe, continued access to safe drinking water is less of a problem, and there is considerable interest in the subject under study. In North America, the United States stands out as the country most interested in the subject, facing a problem of safe drinking water supply that affects between 5 and 10 million inhabitants. Finally, in South America, Brazil and Colombia show minimal interest in the subject and face a significant challenge in the supply of safe drinking water, affecting between 10 and 50 million inhabitants.

In summary, the correlation presented in Figure 6 reveals important regional patterns. However, the lack of data for countries with significant research activity limits the full understanding, especially in Asia, Oceania, Central America, and Africa. Europe shows less of a drinking water access problem and a strong interest in the topic, while in North America, the United States leads in interest, but faces significant supply challenges. Finally, in South America, Brazil and Colombia have minimal interest and face major challenges in safe water access, highlighting the regional complexity of water resource management and the need for more robust approaches to developing solutions.

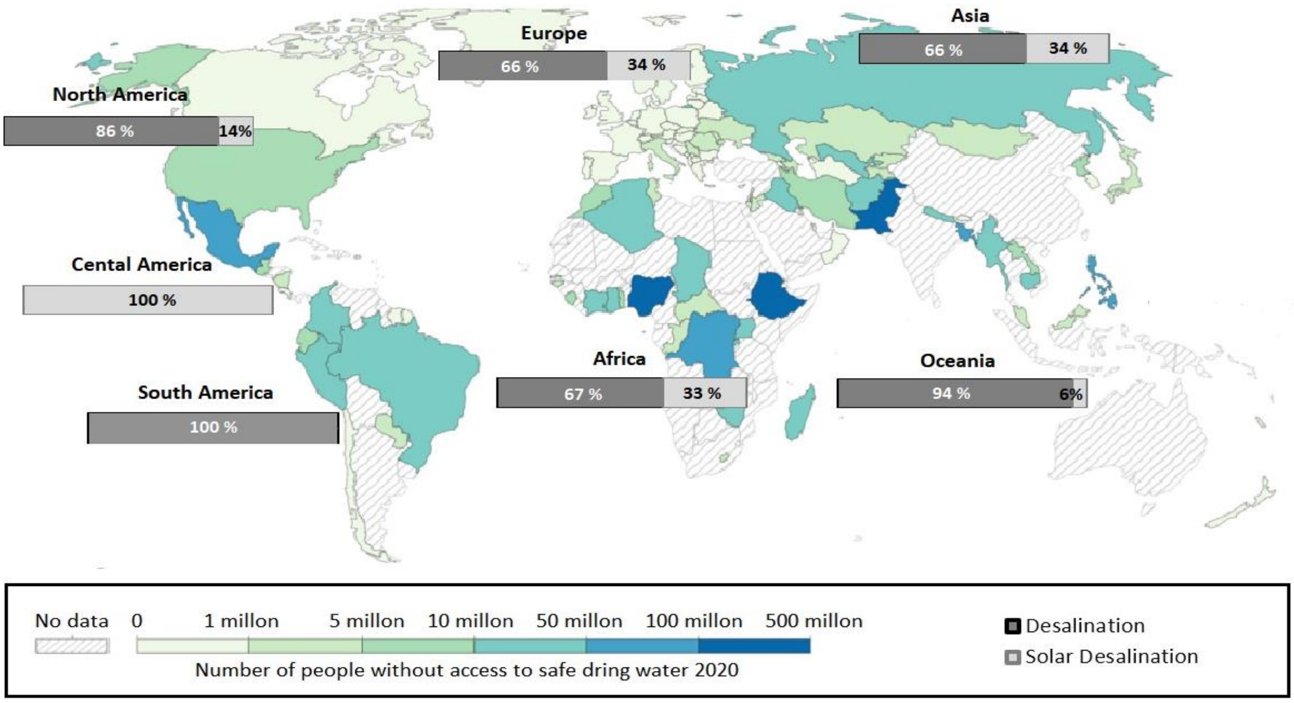


Figure 6. Correlation of population without access to safe drinking water by 2020, jointly presented by the WHO and UNICEF, with the total percentage of LCA papers on desalination and solar desalination analyzed in this study during the period 2015-2024 for each continent

Finally, Figure 7 correlates the global GDP map presented by the World Bank in the year 2021, with the total percentage of Life Cycle Assessment (LCA) documents on desalination and solar desalination evaluated in this study during the period 2015-2024 for each continent. In North America, the United States shows the highest interest in the subject of study and, in turn, has a high GDP. Although Qatar and the United Arab Emirates share high GDP ranges like the United States, this does not determine the incidence of Asia as a continent with high GDP and interest in the topic of study, as Saudi Arabia has a lower GDP, and China has an even lower one.

In Europe, Australia, and Oceania, despite the variability of GDP between countries in each continent, this does not turn out to be a relevant indicator. This is because the countries interested in the topic of study show a high

GDP, mainly due to nations such as the United States, Qatar, and the United Arab Emirates. In South America and Africa, the countries interested in the topic of study have a GDP similar to that of China. However, while in South America, GDP remains relatively constant for most of the countries that compose it, in Africa, areas with high poverty are observed.

In general, the trend in the correlation described above is that interest in solar desalination and desalination seems to be associated with more developed economies with high GDP per capita, such as the United States, Qatar, and the United Arab Emirates. However, the relationship is not direct, as other countries with similar GDP per capita, such as Saudi Arabia, do not show the same level of interest. Furthermore, it is observed that in regions such as South America and Africa, where GDP per capita is lower, interest in the topic is also lower, with additional variations in Africa due to the presence of areas with high poverty.

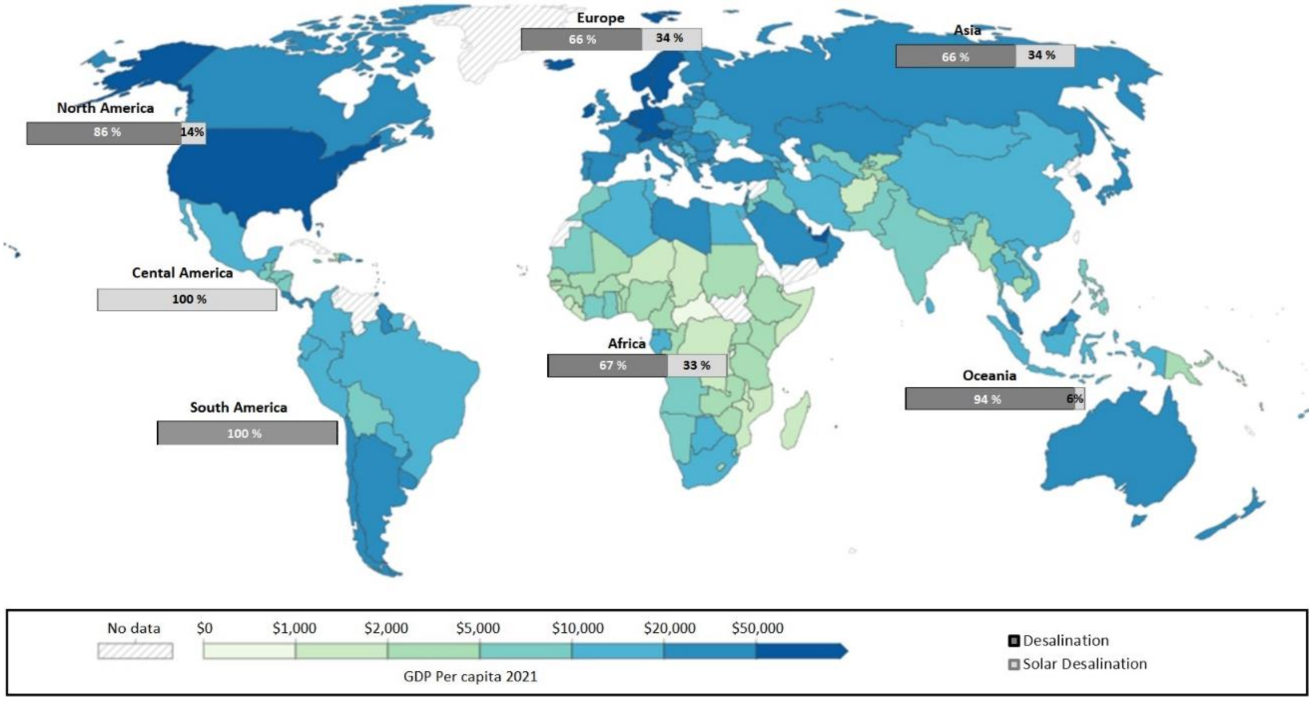


Figure 7. Correlation of the global GDP map presented by the World Bank in the year 2021, with the total percentage of LCA documents on desalination and solar desalination evaluated in this study during the period 2015-2024

In general, the correlation between the topic of study, which covers life cycle assessment applied to desalination and solar desalination, and the factors of solar radiation, GDP, and access to drinking water reveals distinctive trends across continents. It is observed that in Asia, Europe, North America, Oceania, and Africa, countries with high levels of solar radiation tend to show greater interest in these studies, while in Central and South America, where radiation levels are varied, interest in the subject is lower in general. On the other hand, in Europe, where access to drinking water is less problematic, and in North America, where the United States leads in interest, there is greater relevance in the subject. In addition, there is a tendency to associate interest in desalination and solar desalination with more developed economies with a high GDP per capita, such as the United States, Qatar, and the United Arab Emirates. However, the relationship is not direct in all cases, and variations stand out in regions such as South America and Africa, where GDP per capita is lower and interest in the subject is also lower, especially in areas with high poverty. In summary, although solar radiation seems to influence interest in these studies in many parts of the world, factors such as access to clean water and economic development also play important roles and vary by region.

### 3.2. Drawing on LCA studies about solar desalination systems

From the exploratory phase, a growing interest in the academic world on the topic of assessment during the last decade was identified, with assessment in relation to Life Cycle Assessment (LCA) studies applied to desalination and solar desalination technologies. Based on this, we delve into the papers that focus their LCA study on solar desalination technologies in the last 10 years, specifically with 28 papers. However, the first paper linking an environmental analysis, desalination, and solar energy was published in 2012 by [25], and the term LCA appears two years later, applied to a desalination plant [26] and to a solar still [27].

In this context, Fig presents the analysis of the co-occurrence of terms for the relationship between Life Cycle Assessment (LCA), desalination, and solar energy use for the period from 2015 to 2024. Terms such as "reverse osmosis", "distillation", and "economic analysis" stand out, used from 2020, suggesting a higher degree of maturity and research directed to these technologies, especially in economic aspects. In addition, the term LCA gained relevance in 2021, being associated with "desalination" and "solar energy", and gave rise to the term "solar desalination". Likewise, keywords such as "membranes", "sustainable developments", and "environmental impacts" emerge strongly from the second half of 2021, indicating areas of knowledge that require greater attention in future research.

In addition, the recent incorporation of the term "carbon dioxide" suggests that efforts in the life cycle analysis of desalination and solar desalination technologies are not only aimed at addressing the environmental problem caused by brine, but also at reducing the carbon dioxide emissions associated with the process. Finally, it can be stated that membranes represent the emerging technology with the greatest potential to reach technological maturity in desalination processes in the coming years.

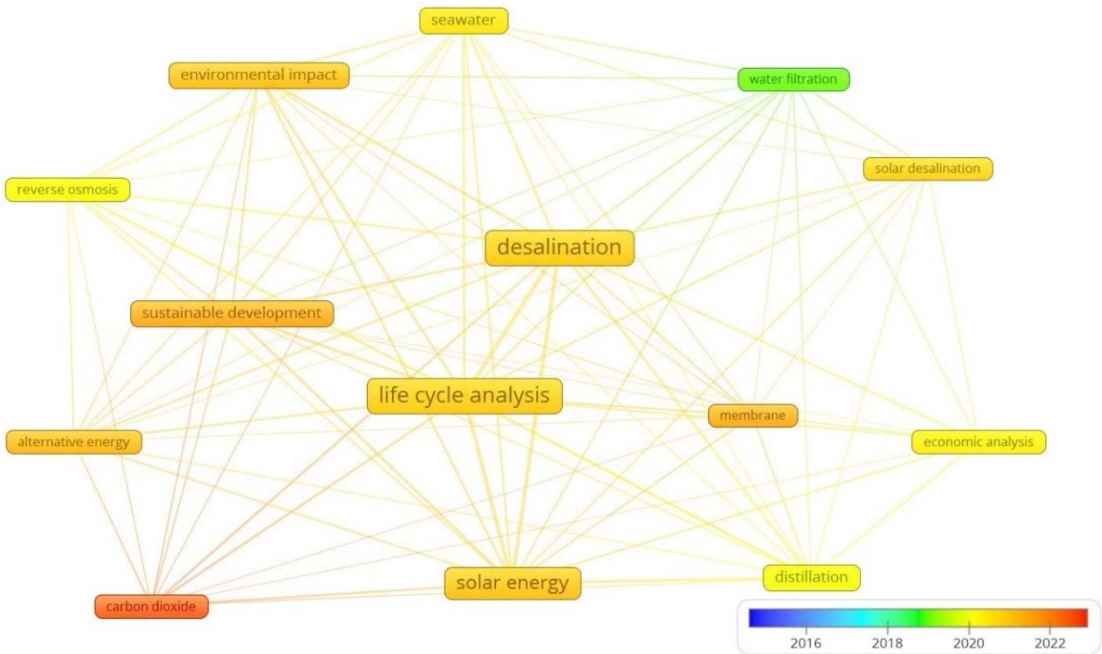


Figure 8. Co-occurrence analysis of terms for the relationship between LCA, desalination, and desalination for a 10-year period

Further analysis using the LCA method applied to solar desalination technologies reduced the set of documents to 28, including 24 articles, 2 reviews, 1 book chapter, and 1 conference. This last type of document was not considered. In the book chapter by [28], a detailed overview is provided of desalination technologies and their integration with renewable sources as an alternative to reduce environmental impacts, with a theoretical disclosure approach. In addition, the authors detail the life cycle analysis process applied to desalination technologies, focusing on reverse osmosis membranes.

However, when broadening the perspective of the research focused on the publication of articles and reviews, it is noted that not all authors have explored the relationship between LCA and solar desalination in their work. This observation is reflected in Table *2*, which highlights 14 papers that address topics that deviate from the main objective of the bibliometric analysis. This thematic diversity underscores the importance of carefully discerning and selecting relevant sources in any research study.

Table 2. List of authors who do not relate life cycle analysis to solar desalination in their work.

| Author | Subject |
|---|---|
| [29] | Research to determine the thermal performance and economic viability of using solar stills in water desalination |
| [30] | Application of solar energy and polymer for water desalination |
| [31] | Application of life cycle analysis to photovoltaic systems, wind systems, and pumping systems for desalination |
| [32] | A mathematical model formulated to optimize the desalinated water production policy |
| [33] | Proposal for an optimization of reverse osmosis plants using renewable energy sources |
| [34] | Study of new coating materials to improve efficiency in solar stills |
| [35] | Study of life cycle conversion efficiency in pyramid-shaped solar stills |
| [36] | Energy analysis, exergy, exergy-economics, and environmental exergy (4E) in Poly generation systems; Based on Integration of GT-Absorption Chiller-Solar PTC-MED-TVC-RO. |
| [37] | Energy and Exergetic analysis of a Concentrated photovoltaic/thermal (CPV/T) system integrated with Vacuum Multi-effect membrane distillation (V-MEMD) |
| [38] | Comparative life cycle assessment of the uranium recovery process from brine. |
| [39] | Metal-organic frameworks applied to water adsorption |
| [40] | Comprehensive performance assessment of water and energy production technologies through water-energy linkage analysis |
| [41] | Techno-economic and environmental evaluation of direct air capture with solar energy |
| [42] | Analytical study of the effect of different photovoltaic technologies on the environmental and economic parameters and energy metrics of an active solar desalination unit |

Finally, Table 3 presents an analysis according to the important aspects of LCA in solar desalination for a total of 12 papers as follows: (i) Location, (ii) Scope of Study, (iii) Methodology, (iv) System Type, (v) Research subject, and (vi) Impact assessment. The impact categories to be included in the analysis presented in Table *3* were selected on the basis of their fulfillment by at least one paper.

The analysis of methodological trends in the Life Cycle Assessment (LCA) of solar desalination systems reveals a wide diversity of approaches adopted by the studies collected. A remarkable participation of the Asian continent in these investigations stands out, with multiple studies conducted in countries such as China, Qatar, Saudi Arabia, the United Arab Emirates, Jordan, the Philippines, and Israel. On the other hand, there is less interest from the European and African continents. In addition, the widespread use of SimaPro software compared to Gabi to carry out the environmental and energy impact assessment of these systems stands out, suggesting its prominence in the scientific community in this field. The scope of study ranges from environmental analysis to the consideration of economic and energy aspects.

In addition, it is noted that the most commonly used methodology for these studies is ReCiPe 2016, followed by MPACT 2002+ and the IPCC 2013 approach. The most evaluated desalination technologies include reverse osmosis (RO), multi-stage flash (MSF), and multi-effect distillation (MED) systems. With respect to the impact categories evaluated, the consideration of Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) stand out, these being the most recurrent in the studies analyzed.

Table 3. Methodological trends in LCA of solar desalination systems*

| Author | Location | Scope of Study | Methodology | | | System Type | Research subject | Impact assessment | | Impact Categories | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Software | Method | System boundary | | | End-point | Mid-point | TETP | METP | WPD | FDP | UIEN | OTP | HTP | POCP | AP | EP | GWP100a |
| [43] | United Arab Emirates,<br>Qatar,<br>Saudi Arabia | Environmental | NA | IPCC 2013 | NA | PVT<br>VC<br>Biomass Boiler | Integration | NA | NA | | | | | | | | | | | ✓ |
| [44] | China | Environmental | SimaPro | IPCC 2013 | NA | 3D photothermal Composite material | Integration and comparison | NA | NA | | | | | | | | | | | ✓ |
| [45] | United Arab Emirates | Environmental | SimaPro | IMPACT 2002+ | Gate to gate | SWRO<br>WT<br>TG<br>FC | Integration and comparison | ✓ | ✓ | Considers all of the Impact Categories | | | | | | | | | | |
| [46] | Spain | Environmental | Gabi v9.2 | ReCiPe 2016 | Cradle to grave | RO<br>MD | Comparison | | ✓ | Considers all of the Impact Categories | | | | | | | | | | |
| [47] | China | Environmental | SimaPro v.9.1 | NA | Gate to gate | Photothermal Biomass aerogels-SSG<br>PV-RO | Integration and comparison | | ✓ | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [48] | Spain | Environmental, economic, and energy | SimaPro v.9.0 | IPCC 2013 | Cradle to cradle | PV<br>PVT<br>MED<br>RO | Integration and comparison | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| [49] | Qatar | Environmental | Gabi | ReCiPe 2016 | Cradle to grave | MED<br>LFC<br>PTC | Integration and comparison | | ✓ | - | - | ✓ | ✓ | - | - | ✓ | ✓ | - | - | ✓ |
| [50] | Jordanian | Environmental | SimaPro v.9.0 | ReCiPe 2016 | Cradle to gate | SPMD<br>CMD | Comparison | | ✓ | Considers all of the Impact Categories | | | | | | | | | | |
| [51] | Saudi Arabia | Environmental and energy | SimaPro v.9.1 | ReCiPe 2016 IMPACT 2002+<br>IPCC 2013 | Cradle to grave | MSF<br>MED<br>RO<br>Solar energy<br>Wind Energy<br>NC<br>Energy<br>Natural Gas | Integration and comparison | ✓ | ✓ | Considers all of the Impact Categories | | | | | | | | | | |
| [52] | Philippines | Environmental | Gabi V.7.3 | ReCiPe 1.08 | Cradle to grave | CSGDBW | Comparison | | ✓ | Considers all of the Impact Categories | | | | | | | | | | |
| [53] | Spain<br>Israel | Environmental | Gabi v6 | IPCC equivalence factors Calculation | Gate to gate | EDBM<br>SWRO<br>PV | Integration and comparison | | ✓ | - | - | - | - | - | - | - | - | - | - | ✓ |
| [54] | South Africa | Environmental | SimaPro v.8.1 | ReCiPe | Cradle to grave | RO | Comparison | | ✓ | Considers all of the Impact Categories | | | | | | | | | | |

*Abbreviatures: Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Human Toxicity Potential (HTP), Other Toxicity Potentials (OTP), Use Energy Indicator(s) (UIEN), Fossil fuel depletion potential (FDP), Water depletion potential (WDP), Marine ecotoxicity (METP), Terrestrial ecotoxicity (TETP), Solar steam generator (SSG), Parabolic trough collectors (PTC), Linear Fresnel collectors (LFC), Solar-powered (SP), Membrane distillation (SPMD), Membrane distillation (CMD), Reverse Osmosis (RO), Membrane Distillation (MD), Graphene oxide (GO), Multi-stage flash distillation (MSF), Multi-effect distillation (MED), Concentrated photovoltaic/thermal (CPV/T), Vacuum Multi-effect membrane distillation (V-MEMD), Conventional Pyramid Still (CPS), Shaded Pyramid Still (SPS), Electrodialysis with bipolar membranes (EDBM), Seawater reverse osmosis (SWRO), Photovoltaic (PV), Natural gas (NG), Heavy oil (HO), Gas oil (GLO), Crude oil (CO), Energia Nuclear (NC), Low temperature Multi-effect distillation (LT-MED), Thermal energy storage (TES), Distributed concentrating solar combined heat and power (DCS-CHP), low-pressure reverse osmosis (LPRO), Photovoltaic-thermal solar collector (PVT), Tidal generator (TG), Wind turbine (TW), Contributions of surface, ground, desalinated and bottled water (CSGDBW)

Note: The system boundaries are based on four options: (i) cradle to cradle, (i) cradle to gate, (iii) gate to grave, and (iv) cradle to grave. In this context, option (i) evaluates only the raw material extraction process, option (ii) evaluates from the raw material extraction procedure to the operation of the system, option (iii) evaluates the operation of the system together with the end of life of the system and finally, option (iv) evaluates the whole life cycle of the system.

### 3.3. Recommendations

To advance the optimization of solar desalination technologies from a sustainability perspective, it is crucial to standardize Life Cycle Analysis (LCA) methodologies. This will allow for greater comparability of studies by clearly defining system boundaries and selecting consistent impact methods. In addition, the expansion of updated environmental databases is essential to accurately capture regional particularities, such as carbon emissions, energy consumption, and brine management.

On the other hand, it is recommended that priority be given to the development of emerging technologies and their implementation in strategic regions with high solar radiation and scarcity of drinking water, where these solutions can have an immediate impact. Finally, it is essential to address brine management, promoting research that minimizes the negative effects on marine ecosystems through innovative solutions, such as mineral recovery. These joint actions can drive the sustainable development of solar desalination globally.

## 4. Conclusions

Water scarcity in several regions of the world has driven the need to develop and implement desalination technologies. Although the solar desalination process has the potential to generate large quantities of fresh water, it is widely recognized that it also entails a number of significant environmental impacts. These include impacts on marine ecosystems and the sea itself, changes in land use, air pollution, and intensive energy consumption, among others.

In this context, it is crucial that environmental assessments accompany the development of solar desalination technologies to ensure sustainable planning. Therefore, this study focused on performing a bibliometric analysis of the application of Life Cycle Assessment (LCA) in solar desalination technologies. From this analysis, the following conclusions were drawn:

i. Since the first publications relating LCA to desalination technologies a decade ago, there has been a steady growth in the number of annual publications on this topic. In the last five years, there has been a clear trend towards an increased focus on the application of LCA to solar desalination technologies. However, the paucity of citable years in these publications has limited their scientific dissemination.
ii. The correlation between LCA applied to desalination and solar desalination, and the factors of solar radiation, GDP, and access to safe drinking water, reveals significant patterns in different regions of the world. Regional complexity in motivation and priorities regarding solar desalination and solar desalination is observed, where factors such as natural resource availability, challenges in access to safe drinking water, and economic development play important roles and vary by region. These findings highlight the need for more robust approaches to address water resource management challenges and the development of solutions in different parts of the world.
iii. The co-occurrence analysis of terms revealed an increasing focus on economic and technological aspects, highlighting terms such as "reverse osmosis" and "economic analysis" since 2020. In addition, the emergence of terms such as "membranes" and "sustainable developments" indicates areas of research where further attention is required. These developments suggest a broader focus on assessing

the environmental and economic impacts of these technologies, with membranes as an emerging technology with significant potential for technological maturity in the coming years.

iv. The studies collected show a diversity of methodological approaches used in the life cycle assessment of solar desalination systems, highlighting the prevalence of the ReCiPe 2016 methodology and a wide variety of desalination technologies assessed. The most evaluated impact categories reflect a concern for environmental effects such as global warming, acidification, and eutrophication, indicating an interest in understanding and mitigating the environmental impacts associated with these systems

v. As expected, Reverse Osmosis technology, due to its wide application and efficiency in water desalination, is the one with the highest number of publications related to LCA. In general, there is a trend toward holistic consideration of all stages of the life cycle of these systems, from conception to final disposal. This holistic approach reflects the growing interest in contributing to the development of more sustainable and efficient solar desalination solutions for the future.

These findings confirm the growing interest of researchers in the application of LCA in desalination technologies, thus reaffirming the imperative need to continue developing sustainable technologies for this process. Finally, the methodology employed in the data analysis has proven to be a highly suitable tool for assessing large volumes of related information using specific keywords. This methodology serves as a crucial initial step to obtain an overview and identify specific trends in recent years.

## Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.


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## Author contribution

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