Evolution of desalination research and water production in the Middle East: a five-decade perspective

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Abstract

Rapid urbanization and population growth, coupled with depleting groundwater reservoirs, have significantly increased reliance on desalination technologies in the arid Middle East, which accounts for nearly half (46%) of global desalination capacity. This large production volume has raised critical questions on the status of desalination research in this water-stressed region, and on whether it aligns with the pace of industrial production. We conducted a systematic review that collated 2,718 publications produced over five decades (1972-2022). Subsequently, we employed scientometric analyses to assess research parameters such as temporal trends in publication, research themes, authorship trends and technological advancements. This review was then followed by statistical analyses comparing regional scientific output with other economic, demographic and water stress metrics to identify correlations between desalination research and water production. Our findings revealed dramatic growth in desalination research since the early 2000s, with 83% of historic papers published just in the last decade (2013-2022). Over half of publications focused on research themes related to energy efficiency, regulatory concerns and cost-benefit analyses. The technological focus shifted from thermal to membrane technologies over time, mirroring trends in industrial applications. Authors affiliated with regional institutions emerged as primary contributors, which is in stark contrast with other research fields. In terms of economic factors, national GDPs showed a positive correlation with both publication volume and desalination capacity. This review underscores desalinations' critical role in regional water security, highlighting the need for targeted innovation and cross-sector collaboration to address current and future water stress challenges.

Keywords: Desalination; Scientometric Analysis; Research Trends; Authorship Trends; Middle East; Water Production; Technological Advancements.

Highlights

- 83% of historic desalination research occurred in the last decade, growing rapidly
- Energy efficiency, regulations, cost-benefit analysis dominate research themes
- Research shifted from thermal to membrane technologies, mirroring industry trends
- Local institutions lead in contributions to regional desalination research
- GDP strongly correlates with publication volume and desalination capacity

1. Introduction

Conventional water resources such as rivers, lakes, snow melt and groundwater are increasingly inadequate to sustain growing demands for water in many parts of the world (Lee & Jepson, 2021; Jones et al., 2019). The Intergovernmental Panel on Climate Change estimates that roughly half of the global population currently experiences extreme water shortages for at least a portion of the year, with forecasts predicting this figure to reach 60% by 2050 (Boehm et al., 2023; IPCC, 2023). Water shortages are especially acute in the Middle East (also known as South West Asia), an arid and semi-arid region grappling with increasing populations, rapid urban expansion and industrial development, where 83% of inhabitants have been identified as vulnerable to fluctuations in water quantity, quality and accessibility (Boehm et al., 2023). Moreover, evidence suggests that 65% of the most water-stressed countries in the world are situated in the Middle East, including Bahrain, Iran, Jordan, Kuwait, Lebanon, Libya, Oman, Palestine, Qatar, Saudi Arabia and the United Arab Emirates (FAO, Aquastat, 2022). These conditions are expected to be further exacerbated by climate change, unsustainable water consumption and transboundary water disputes (Sowers et al., 2011). In response to this growing water stress, the Middle East has increasingly turned to desalination to support water demands—a process that involves the removal of dissolved salts and other minerals from non-potable water sources, including brackish water, seawater, greywater and wastewater (Nair & Kumar, 2013).

Recognizing that desalination has been practiced on small scales throughout human history (Asli et al., 2023), it was only with the onset of the industrial revolution and the commercialization of oil and gas in the late 1930s that large-scale production and transportation of desalinated water became feasible. Countries in the Middle East were among the first to leverage this technology to address their water requirements at scale (Roberts et al., 2010; Qadir et al., 2007). For instance, as early as 1907, Saudi Arabia retrieved and installed a coal-powered desalination machine from a shipwreck off the shores of Jeddah (CareWater Tech Solutions, 2021). Two decades later, in 1926, the country imported two desalination plants to meet the needs of pilgrims and Umrah performers (Low, 2015). Kuwait, in parallel, became the first country in the world to pioneer the multi-stage flash distillation system in 1957, followed by Qatar in 1960 (Darwish et al., 2011; Boussaa, 2014; Rahman & Zaidi, 2018). Moving forward to 2023, and the Middle East houses just under half of the global desalination capacity (45.9%), each day producing 68 million cubic meters of desalinated water (GWI, 2022); many Gulf countries have plans underway to double capacity by 2030 to alleviate anticipated increases in water stress (Paparella et al., 2022). Though the region has reached a stage where it can reliably use desalination to produce potable water at prices comparable to conventional water sources (Dawoud, 2005), regional geographic disparities in production persist. These disparities are likely due to country-level variations in fresh water supplies, finances, affordable energy sources and water allocation rights (Sayed et al., 2023). While innovations in desalination technology—such as solar-powered desalination units installed in rural areas—are assisting lower-resourced countries in increasing water supply, these geographic disparities have remained in the wake of growing pressures and droughts.

Advances in the modern era of desalination would not have been possible without desalination research, considered critical in identifying innovative solutions for water security, energy efficiency and environmental sustainability. However, no study to date has offered a synoptic view of the peer-reviewed scientific evidence on desalination across the Middle East, except for Zyoud and Fuchs-Hanusch (2015), who relied exclusively on a bibliometric analysis to examine desalination research productivity trends in the region. Therefore, there is a clear need to offer a more up-to-date assessment of the status of desalination research that fills this decadal temporal gap, but also a need to investigate research trends and their associations with industrial production capacities with greater precision and depth. As such, this study seeks to: first, conduct a systematic review to rigorously search, categorically synthesize and comparatively analyze the historical trends in desalination research across the 17 countries/nations (hereafter referred to as the 'Middle East') bordering the four marine provinces surrounding the Arabian Peninsula—the Red Sea and Gulf of Aqaba, the Western Arabian Sea, the Oman Sea and the Arabian/Persian Gulf (hereafter, 'the Gulf'). Second, we aim to investigate the changes in water production volumes and desalination technologies within the Middle East, drawing on information extracted from the Global Water Intelligence database (GWI, 2022). Lastly, we statistically analyze the relationship between scientific publication output and water production to better understand the association between research and industrial activity. This study builds on previous global literature reviews on desalination (Zapata-Sierra et al., 2021;

Chowdhury et al., 2024; Belmehdi et al., 2023), which have predominantly relied on bibliometric analyses based exclusively on keywords and metadata from citation databases such as *SCOPUS* and *Web of Science*. While these global reviews provide valuable insights, they often adopt a narrow, metrics-focused perspective that lacks a comprehensive examination of the underlying evidence base. Similarly, this study consolidates Middle East-centered reviews of desalination, which have been limited in scope and often concentrating on specific research topics such as ‘renewable energy’ (Al-Karaghouli et al., 2009; Mahmoudi et al., 2023; Sayed et al., 2023) or the ‘water-energy nexus’ (Maftouh et al., 2022), or restricting their focus on isolated countries and subregions, such as the Gulf Cooperation Countries (Elsaie et al., 2023; Moossa et al., 2022).

By examining trends in desalination literature—such as publications by country, research themes and technological applications, and evaluating their relationship with desalination production capacities, this review offers valuable insights and guidance to all stakeholders in the desalination field. Our findings aim to foster collaboration and innovation to address the region’s growing water crisis, while identifying region-specific research gaps and misalignments between academic foci and industrial production.

Methods

2.1 Trends in research productivity

This systematic review used *SCOPUS*, one of the largest abstract and citation databases with stringent content selection policies (Ballew, 2009), to identify peer-reviewed scientific literature on desalination focusing on the Middle East, published in English or Arabic, up to the 31st of December 2022. Other databases were not embedded to maintain consistency with global desalination reviews such as Zapata-Sierra et al. (2021). The geographic parameters were restricted to the 17 countries/nations bordering the Red Sea and the Gulf of Aqaba, the Gulf and the Western Arabian Sea (including the Oman Sea to the Iran-Pakistan border and the Gulf of Aden to Puntland in northern Somalia) (Fig. 1 and Table S1 for the full list of countries/nations and geographic groupings used across the study). The search query consisted of the term ‘desalination’ combined with the names of all the relevant areas and marine provinces surrounding the Arabian Peninsula: “(TITLE-ABS-KEY ("Desalination") AND TITLE-ABS-KEY ("Bahrain" OR "Egypt" OR "Eritrea" OR "Iran" OR "Iraq" "Israel" OR "Jordan" OR "Kuwait" OR "Oman" OR "Palestine" OR "Qatar" OR "Djibouti" OR "Saudi Arabia" OR "Somalia" OR "Sudan" OR "United Arab Emirates" OR "Yemen" OR "Red Sea" OR "Arabian Gulf" OR "Persian Gulf" OR "Gulf of Aqaba" OR "Gulf of Eilat" OR

"Gulf of Oman" OR "Arabian Sea" OR "Sea of Oman" OR "Strait of Hormuz")) AND PUBYEAR < 2023”. Publications partially related to the region were included (e.g., if the Middle East was a regional component in a larger global study). Books and book chapters were also incorporated into the dataset when accessible for content verification. All entries were collated and verified in Microsoft Excel, with duplicates, retractions, not-accessible and out-of-scope papers removed prior to analyses (Table S2 ‘Exclusion rationale’ for details). Each paper was independently assessed and screened by two different authors (M.A.M. and A.A.G.), with a third screener (D.D.) intervening in cases of disagreement.

To explore geographic and temporal trends in research, the reviewed articles, books and book chapters were categorized using scientometric analysis to allow for comparisons across the dataset. Publications were first classified by location: ‘Studied Country’ (including ‘Multiple’ for multi-national research), indicating the focal country of the desalination research; and ‘First-Author Institution’ and ‘First-Author Region’, which reflected the physical location of the lead researcher at the time of publication, thereby identifying the country or region hosting the research project. Publications were further classified by ‘Research Theme’ (Table 1 and Table S3 ‘Research Theme details’) and ‘Desalination Technology’ (Table 2), in order to highlight the evolution of research topics and desalination technologies over time. While other reviews have broadly classified desalination research themes using automated categories from *SCOPUS* and *Web of Science* (e.g., ‘environmental science’, engineering’, ‘chemistry’, etc.) or keywords (e.g., ‘membranes’, ‘seawater’, ‘water filtration’, etc.) (Zapata-Sierra et al., 2021; Chowdhury et al., 2024), our review provides a more in-depth and precise analysis by applying an adapted version of the US Bureau of Reclamation’s (2014) thematic framework for desalination research priorities (Table S3). Because only one publication was recorded before 1973 (Shelef et al., 1972), this single record was excluded from the analysis.

2.2 Trends in water production

Data for assessing trends in desalinated water production were obtained from the Global Water Intelligence database (GWI, 2022), which provides detailed information on desalination plants, including their operational status, year of operation or decommission, water production capacity (m^3 d^{-1}), geographic location and desalination technology, spanning from 1950 to 2027. In this study, we considered the desalination plant status as: ‘operational’ if classified by GWI as either ‘online’ or ‘presumed online’; ‘not operational’ if classified as ‘offline’ or ‘presumed offline’; and ‘new by 2027’ if classified as ‘in construction’, ‘planned’ or ‘awarded’. The year of operation or decommission refers to the year in which the plant became operational or ceased operation, and this information was used to calculate the net water production capacity per year. Geographic location data were used to allocate desalination capacity to each geographical entity and plant. Global desalination plants were grouped into six geographic regions: 1) Africa; 2) Europe & Central Asia; 3) Latin America & Caribbean; 4) Middle East; 5) North America; and 6) South East Asia (Table S1), to allow contextualization of desalination in the Middle East. Desalination technology was classified using the same categories listed in the systematic review to maintain consistency (Table 2).

2.3 Statistical analysis

Metrics of economic performance (Gross Domestic Product [GDP], sourced from the World Bank, 2023), demography (populations, in millions of inhabitants, from the United Nations, 2022), and water stress (ratio between total freshwater withdrawn by all major sectors and total renewable freshwater resources, from FAO Aquastat, 2022) were used to compare and analyze correlations and linear regressions between desalination research (i.e., the total number of publications) and production (i.e., desalination capacity, $m^3\ d^{-1}$) among the countries/nations included in this study. The datasets provided information on GDP, population, and water stress up to the year 2020. All analyses were performed in R (R studio v 4.3.3, 2024).

Table 1. Criteria for categorizing desalination publications into thirteen research themes (see Table S3 for further details).

Research Theme	General Criteria
Energy Efficiency Technologies	Integrated renewable energy, waste heat recovery and other approaches to reduce energy consumption and increase the efficiency of desalination.
Institutional, Regulatory and Policy Concerns	Elaborated on institutional, regulatory and policy concerns associated with desalination, including establishing independent product testing, documenting permitting issues, assessing environmental impacts, developing public awareness strategies and introducing water conservation policies.
Treatment Improvements	Explored innovative desalination technologies and techniques, membrane advancements and hybrid systems to improve performance and reduce costs.
Pre-Treatment and Anti-fouling Technologies	Developed and evaluated effective pretreatment and anti-fouling technologies and strategies to reduce membrane fouling and improve desalination efficiency.

Cost-Benefit Analysis	Conducted techno-economic analysis and feasibility study on topics ranging from alternative desalination technologies to sustainable energy integration and evaluating the value of water for users.
Water Quality Concerns	Evaluated and addressed water quality concerns related to desalination processes, including contaminant removal, resource recovery, assessing hazards/toxicity and exploring advanced wastewater treatment processes.
Brine Disposal Alternatives	Minimized or mitigated brine disposal impacts by investigating brine injections into depleted oil/gas fields, developing novel zero liquid discharge processes and exploring beneficial reuse of concentrating components.
Vegetation Use	Evaluated the potential of halophyte cultivation and integrated biological processes for salinity control, managing desalination plant effluents and producing potable water.
Distribution System Integration	Assessed and addressed the challenges of integrating desalinated and re-used water into existing water supply infrastructure and using artificial recharge, recovery systems and storage buffers.
Monitoring Improvements	Discussed and/or developed improved monitoring techniques and protocols for desalination processes and water reuse scenarios to ensure preparedness for hazardous events, system failures or bioterrorism.
Intake Improvements	Evaluated and/or improved intake technologies and established methodologies to minimize environmental impacts like impingement and entrainment.
Anthropogenic Impacts on Desalination	Examined the impact of human activities and environmental changes such as climate change, hurricanes, pollution and coastal development on desalination processes.
Other	Studies that fall outside the scope of the above research themes.

Table 2. Classification of desalination technologies (adapted from Khalifa, 2011).

Desalination Processes	**Technology Specification**
Thermal – Evaporation	Multi-Stage Flash (MSF); Multi-Effect Distillation (MED); Thermal Vapor Compression (TVC).
Non-thermal – Membrane Technology	Reverse Osmosis (RO); Forward Osmosis (FO); Electrodialysis (ED); Reverse Electrodialysis (EDR); Micro/Ultra/Nano-Filtration.
Non-thermal – Membrane Distillation	Membrane Distillation (MD).
Renewable – Direct Solar	Solar Stills; Humidification-Dehumidification (HDH).
Multiple	Two or more technologies from different desalination processes were investigated or compared.
Multiple & Hybrid	Two or more technologies from two different desalination processes were developed to work in a hybrid setup.
Other and Emerging	When the technology studied has been detected in the literature less than 10 times ($n < 10$): Phyto-desalination, Microbial Desalination, Freeze Distillation, Desalinating Pipeline, Capacitive Deionization (CDI), Greenhouse Desalination, Chemical Desalination; Adsorption Desalination.
Not Applicable	No technology was investigated.
Not Specified	The paper broadly discussed the topic or elements of desalination technology but failed to list a specific type.

1. Results

3.1 Historical Trends

The *SCOPUS* search yielded a total of 2,718 citations, of which 1,899 (70%) met the criteria for inclusion in this study. The first publication studying desalination in the Middle East was in 1972 (Shelef et al., 1972), yet, before 1998, less than 100 papers were published within each five-year period. This frequency, however, began to shift significantly in the early 2000s, reaching a peak of over 600 studies published in the most recent five years, 2018 to 2022 (Fig. 1). Saudi Arabia, Egypt, Kuwait and Iran were the most frequently studied countries accounting for 20%, 12%, 12% and 11% of the total publications, respectively, together representing over half of all historic published records.

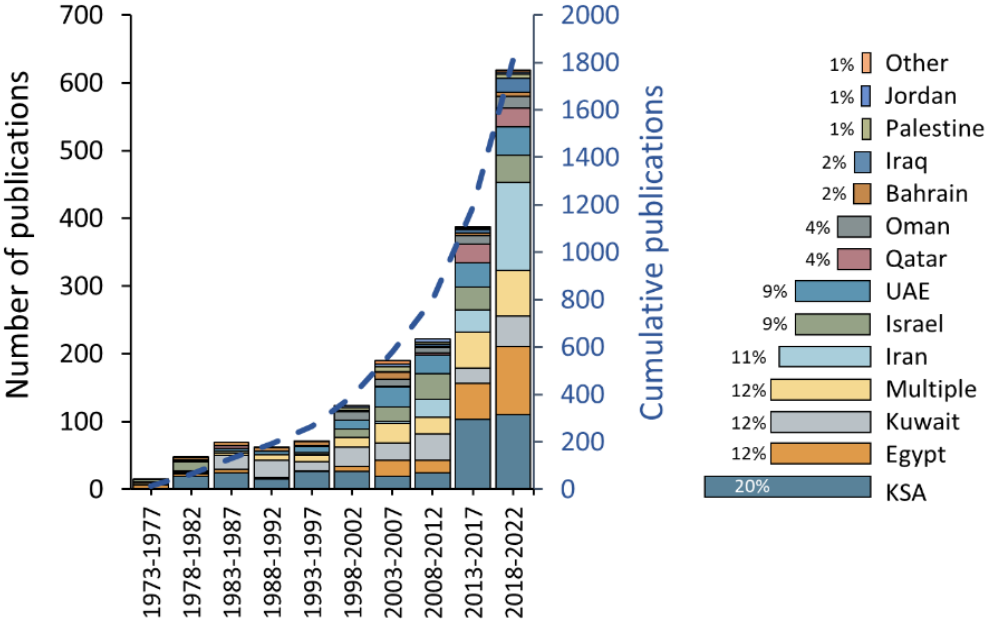

Figure 1. Historical trends in desalination research across the Middle East by 'Studied Country'. Bars represent the number of publications over four-year intervals from 1973 to 2022, grouped by the 'Studied Country'. The dashed line shows the cumulative number of articles over 50 years, while the legend (right) shows the cumulative percentage of publications by targeted country.

3.1.1 Research Themes

To identify historical trends across research topics, all publications were categorized into thirteen major thematic areas, as outlined in Table 1 and illustrated in Figure 2. Overall, publications classified as 'Energy Efficiency Technologies' and 'Institutional, Regulatory and Policy Concerns' were the most common thematic research areas in the Middle East, accounting for almost half of all publications historically produced across the region (24% and 22%, respectively). A further third of research was roughly evenly distributed among 'Cost-Benefit Analysis' (11%), 'Treatment Improvements' (11%), and 'Other' (10%), while 'Water Quality Concerns' and 'Pretreatment and Anti-Fouling Technologies' accounted for 7% and 6% of total publications, respectively. The remaining categories—'Brine disposal alternatives', 'Vegetation use', 'Distribution system integration', 'Monitoring improvements', 'Anthropogenic effects on desalination', and 'Intake improvements'—collectively accounted for less than 11% of publications (Fig. 2, 'All Years').

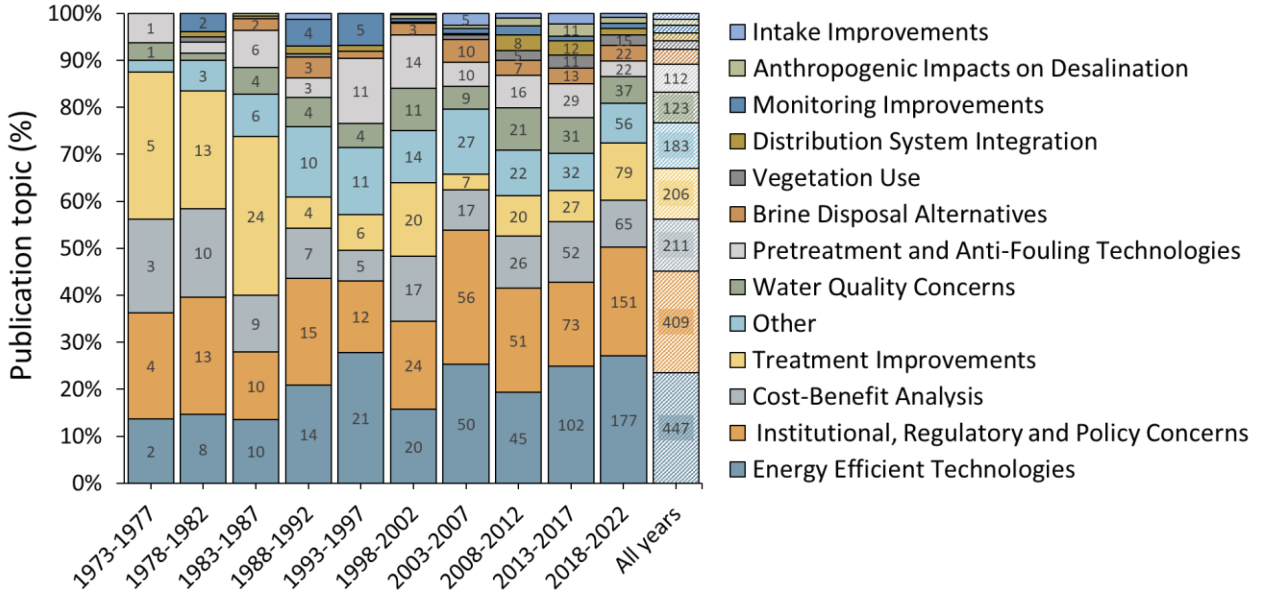

Figure 2. Historical trends in publication topics. Historical trends (%) in publication grouped by 'Publication Topic' over five-year intervals. The last column on the right shows the total number of publications.

3.2 Authorship Trends

Authorship trends revealed that most desalination research was conducted by authors affiliated with Middle Eastern institutions at the time of publication. Contributions from 'local authors' averaged just 60% between 1973 and 1987, with a significant proportional increase from the late 1980s onward, reaching approximately 80% of the research output, on average, since the 1980s (Fig. 3A). Authors from European and Central Asian institutions were the second-largest contributors to historic desalination research in the Middle East, collectively accounting for 12% of the regional literature, followed by contributions from North American (6%) and South-East Asian (4%) institutions. Fig. 3B illustrates the 'flow' of contributions from first authors based in institutions across different geographical macro-regions (i.e., 'First-Author Region') to research outputs targeting each Middle Eastern country (i.e., 'Studied Country'). Most of the research (≥ 70 %) on Middle Eastern countries was conducted by authors residing in the region at the time of publication. In contrast, 51% of papers targeting 'Multiple' countries within the region were produced by external authors, with 28% from Europe and Central Asia, 14% from North America and 7% from South-East Asia (Fig. 3B, Table S4 for details). Additionally, more than 90% of authors based in a Middle Eastern country focused their research on issues specific to their country of residence, except for Jordan (84%) and Palestine (65%) (Table S5).

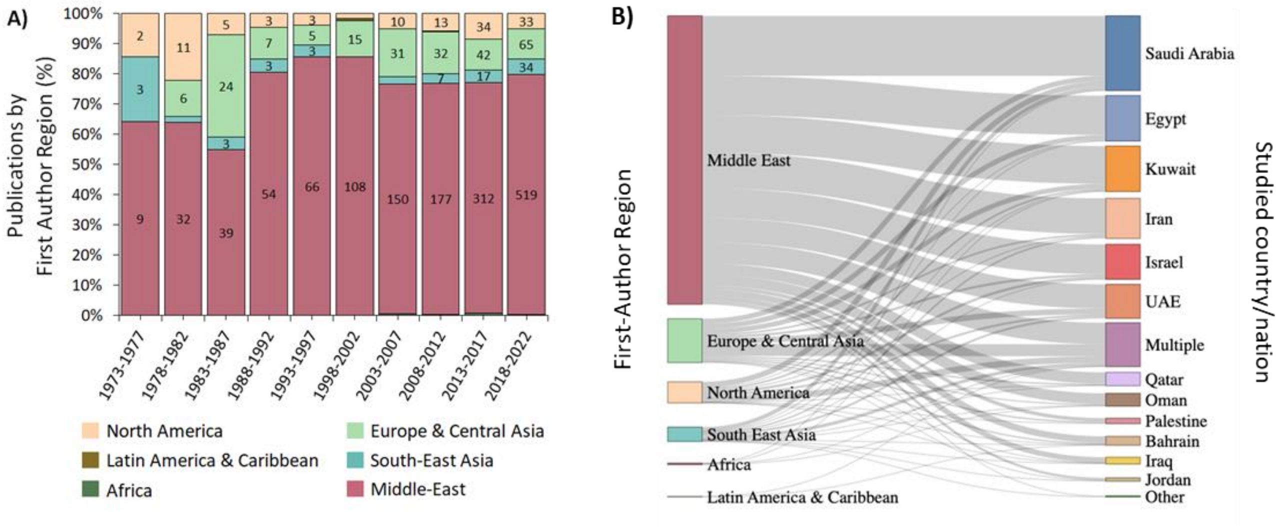

Figure 3. Authorship trends in desalination research in the Middle East. A) Temporal trends in the proportion of publication of studies targeting the Middle East grouped by 'First-Author Region' (i.e., the region where the research institution hosting the lead researcher was located). **B)** Left to right: flow of 'First-Author Region' to 'Studied Country' (i.e., the country target of the research).

3.3 Scientific Productivity & Water Desalination Capacity

Desalination water production capacity and publication quantity differed significantly among the Middle Eastern countries/nations included in this study (Fig. 4, Table S6). In 2022, Saudi Arabia and the UAE had the highest desalination capacity in the region, with 17 and 11 million m^3 d^{-1} of desalinated water production, respectively. Water production was between 3.6 and 1.2 million m^3 d^{-1} in Kuwait, Qatar, Israel, Oman, Egypt, Iran, and Bahrain. Finally, desalination production was modest in Iraq (0.6 million m^3 d^{-1}) and Jordan (0.3 million m^3 d^{-1}), and very limited in Yemen, Palestine, Sudan, and Djibouti, with each producing less than 0.01 million m^3 d^{-1}. Eritrea and Somalia had almost no desalination capacity, with output below 0.001 million m^3 d^{-1}. In contrast, as of December 2022, Saudi Arabia and Egypt led the region in terms of desalination-related research publications, with 319 and 220 peer-reviewed articles, respectively, based on 'First-Author Institution' data. They were closely followed by Iran (n = 192), Kuwait (n = 189) and the UAE (n = 141), while Qatar (n = 73), Bahrain (n = 33), Iraq (n = 26) and Jordan (n = 19) produced fewer publications. In line with their limited desalination production, Sudan, Djibouti, Yemen, Eritrea and Somalia had minimal research activity, with one or fewer publications each over the 50 years studied (Table S6).

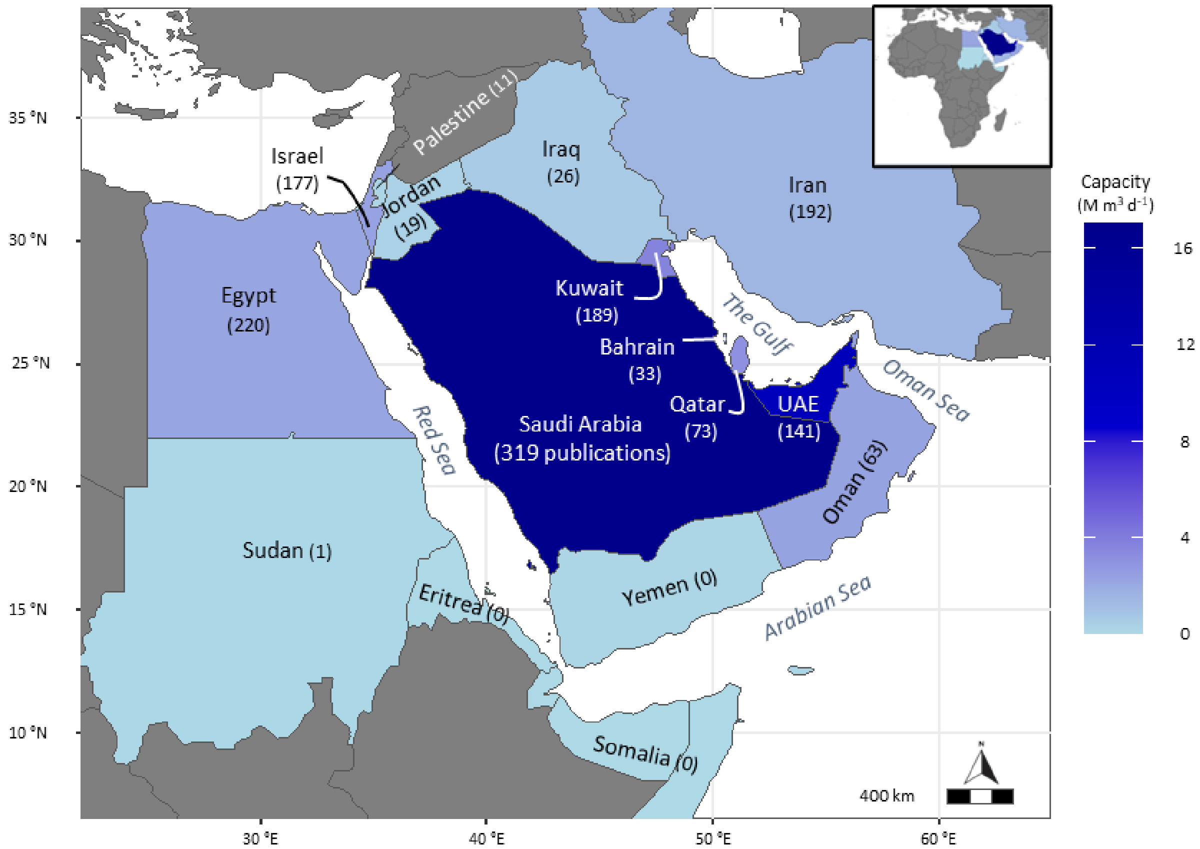

Figure 4. Research productivity and water desalination capacity in the Middle East. Color scale corresponds to desalinated water production capacity (million m^3 d^{-1}) in 2022. Bracketed numbers adjacent to country names represent the cumulative number of publications (as of December 2022) on water desalination research per country (classified by 'First-Author Institution', i.e., the physical location of the institution hosting the lead researcher and, thus, representing the country hosting the research project). *Note: Many borders in this region are contested, which the authors acknowledge. As such, this map does not reflect current geopolitical complexities nor the views of the authors but is based on borders delineated by the R package 'naturalearthdata'.*

3.4 Statistical analyses

Despite socio-economic differences among Middle Eastern countries in key areas such as GDP, population, and water stress (Table S6), GDP was the only variable that showed a statistically significant positive correlation with both publication volume and desalination capacity (GDP : Number of Publications, $r_{[df=15]} = 0.9$, $p < 0.0001$; GDP : Desalination Capacity, $r_{[15]} = 0.83$, $p < 0.001$) (Fig. 5A). These correlations were further elucidated by the strong linear relationships observed between GDP and the number of publications ($y = 6.96 + 1.82\ x$, $R^2 = 0.80$) and GDP and desalination capacity ($y = 65.9 + 36.9\ x$, $R^2 = 0.69$), indicating that greater economic resources enable higher investments in research and desalination infrastructures (Fig. 5B, top left and right panels). Furthermore, a significant and strong positive correlation ($r_{[15]}$ = 0.74, p = 0.01) and a moderate positive linear relationship (y = 43.4 + 16.2 x, R^2 = 0.54) were observed between publication volume and desalination capacity (Fig. 5A and 5B bottom panel), suggesting that countries investing in desalination research are also likely to have substantial desalination infrastructure and vice versa. In contrast, the moderate positive correlation between the number of publications and population size ($r_{[15]}$ = 0.43), as well as water stress levels ($r_{[15]}$ = 0.45), were not statistically significant (p > 0.05). Similarly, desalination capacity showed a moderate but non-significant positive correlation with water stress ($r_{[15]}$ = 0.42) and no correlation with population size ($r_{[15]}$ = 0.03) (Fig. 5A).

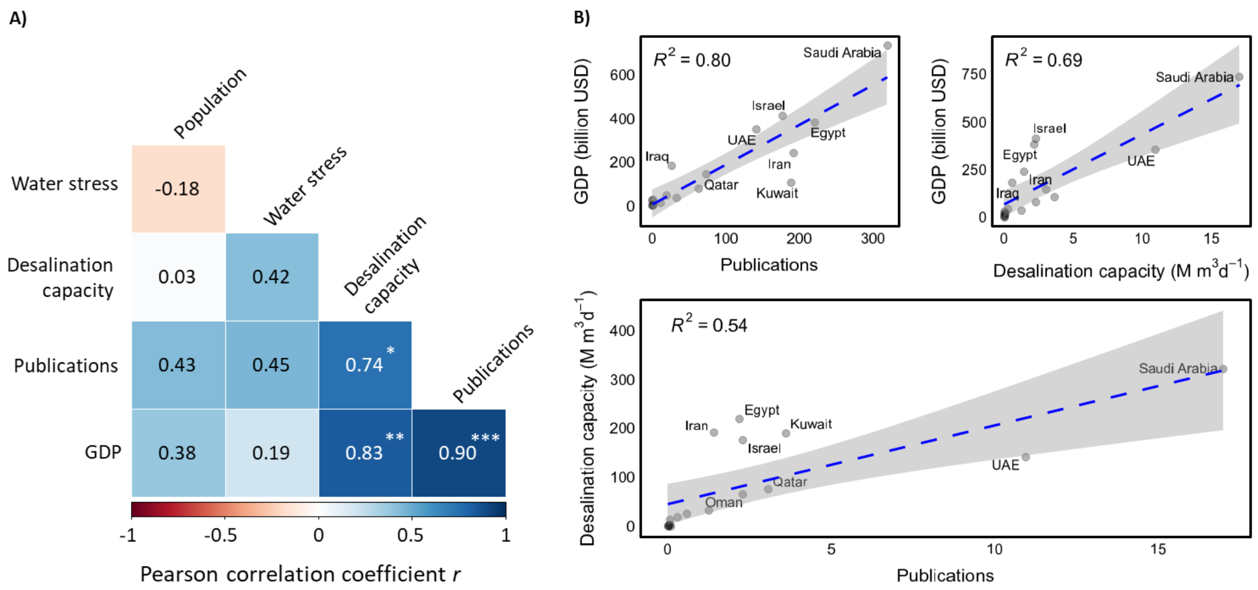

Figure 5. Correlation analysis and scatterplots of population, desalination capacity, number of publications, GDP and water stress. A) Correlation matrix assessing associations between population, desalination capacity, number of publications, GDP and water stress. Numbers indicate the *r* value. Asterisk indicates statistical significance level with * = $p < 0.01$, ** = $p < 0.001$, and *** = $p < 0.0001$. **B)** The three scatterplots display the relationship between publications and GDP (top left panel), desalination capacity and GDP (top right), and publications and desalination capacity (bottom). Each point represents a country, labeled for clarity, with regression lines (blue dashed) showing the linear trend, shaded by the 95% confidence intervals. The R^2 values quantify the proportion of variance explained by the regression model, indicating the strength of the relationships.

3.5 Technology in Research versus Production

Trends in desalination research over the past five decades show a progressive shift from studies on thermal evaporation technologies (i.e., MSF, MED, VC) towards research on membranes (i.e., RO, FO, U/M/NF) and renewable technologies (i.e., Solar Stills, HDH) (Fig. 6A). Specifically, ‘Thermal – Evaporation’ desalination research comprised 41% of the discourse on desalination technologies up until the late 1990s but has since declined to less than 20% between 2013 and 2022. This decline has been primarily superseded by research on ‘Non-thermal – Membrane Technology’, which increased from 33% between 1973-1997 to 45% between 1998-2022. The significant rise in research on ‘Renewable – Direct Solar’ and ‘Multiple and Hybrid’ technologies has also played a role in this shift, with notable growth from 2002 onwards that reached peaks of 22% and 8% in 1998-2022, respectively. This transition from research on ‘Thermal – Evaporation’ to ‘Non-thermal – Membrane Technologies’ has closely mirrored industry trends in water production (Fig. 6B). For instance, newly installed desalination plants using ‘Thermal – Evaporation’ technologies represented 80% of total installed capacity between 1973 and 2002. However, this trend reversed in 2003 (46%) and declined to just 5% between 2018 and 2022. All new plants approved and in construction through 2027 are set to exclusively utilize ‘Non-thermal – Membrane Technologies’. Ultimately, cumulative desalination water capacity has grown exponentially (Kolmorov-Smirnov test on an exponential distribution, $D = 0.0938$, p-value = 0.97) since the late 2000s, rising from less than 10 million $m^3\ d^{-1}$ between 1993-1997 to 45 million $m^3\ d^{-1}$ in 2022. By the end of 2027, desalination capacity is projected to increase to nearly 60 million $m^3\ d^{-1}$ across the Middle East (Fig. 6B). Nevertheless, nearly half of the regional desalination capacity today still depends on ‘Thermal – Evaporation’ technologies, which is in stark contrast with other global regions where >95% of desalination currently relies on ‘Non-thermal – Membrane Technologies’ (Fig. 6C).

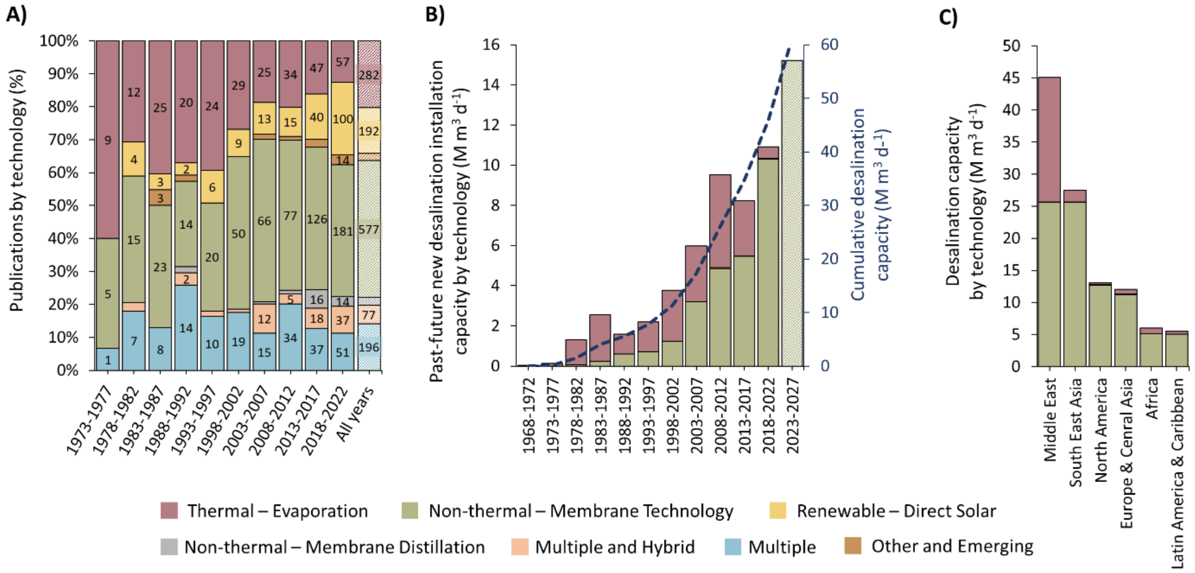

Figure 6. Comparisons between scientific research (publications) and water production (desalination capacity) by technology. A) Changes in percentage of publications by desalination technology over time; **B)** trends in past and future newly installed desalination capacity by technology over time; **C)** comparison between current (i.e., 2022) desalination capacity by technologies between the Middle East and other geographic regions. In A) 502 papers (i.e., 26.4% of the total) were excluded from the analysis as they either did not specify a technology or were off-topic (i.e., related to desalination but not specifically focused on desalination technologies).

2. Discussion

Over the past half-century, and particularly in the past two decades, desalination research and water production have advanced at an unprecedented rate globally. In the Middle East, region-specific characteristics have positioned it as a critical location for research and development of desalination technologies. Factors such as severe water stress and scarcity, above-average per capita water consumption, abundant and low-cost energy reserves from both conventional and renewable sources, early investments in large-scale desalination plants and a political drive towards transitioning to a knowledge-based, green economy have all contributed to this development. The rapid progress in desalination research and production underscores the critical role this technology plays in supporting regional prosperity and security. As climate change intensifies in the coming decades, enhancing droughts and threatening freshwater supply, the importance of desalination in the Middle East will be expected to grow even further.

In this systematic review, we synthesized and analyzed five decades of desalination publications

(1972-2022) to illustrate the historical and geographic trends in research and we statistically compared these trends with the production capacity from desalination in regional nations. By thoroughly categorizing 1,899 peer-reviewed publications, we captured the evolving landscape of desalination research themes, technologies and production capacities among the 17 countries/nations that comprise the Middle East. This approach addressed significant gaps in the literature and identified region-specific research needs and misalignments between academic foci and industrial production. Therefore, while previous reviews have provided useful insights into trends in desalination research (Zyoud & Fuchs-Hanusch, 2015; Jones et al., 2019; Zapata-Sierra et al., 2021;Chowdhury et al., 2024), this study presents a more nuanced and Middle East-specific analysis.

Our findings showed a dramatic growth in desalination research and water production since the early 2000s, with notable shifts in research themes and technologies studied. Strikingly, 83% of all research was published in just the past decade (2013-2022). However, this growth has not been uniformly distributed among the water-stressed regions of the Middle East, being significantly stronger in nations with higher GDPs and larger populations—particularly Saudi Arabia, Egypt, Kuwait, and Iran, which together accounted for 55% of all publications. In contrast, Qatar, Oman, Jordan, Yemen and Palestine collectively had the fewest publications.

Furthermore, over half of publications were concentrated on three of the thirteen research themes: ‘Energy Efficiency Technology’, ‘Institutional, Regulatory & Policy Concerns’, and ‘Cost-Benefit Analysis’. Authors affiliated with regional institutions have consistently been the most prolific contributors to desalination research. Lastly, our analysis indicated that GDP was the only variable that held a statistically significant positive correlation with both publication volume and desalination capacity, indicating the importance of economic capacity both to produce desalinated water in volume and to fund research for future improvements.

4.1 Research Themes

The most recurrent research theme, ‘Energy Efficiency Technology’, focused on reducing energy consumption and inefficiencies in desalination processes. This often involved the integration of renewable energy sources, such as photovoltaic systems and wind turbines, as well as waste heat recovery and other innovative approaches. Analyzing these trends over time revealed that research aimed at improving energy efficiency only became predominant in the Middle East from the 1990s onwards. This shift suggests that regional priorities have evolved beyond reliance on fossil fuels and towards a diversified energy mix, incorporating renewable energy.

This transition has been driven by factors such as market volatility in the energy sector, the pressure to mitigate climate change and a growing awareness of the need to balance water provision with energy sustainability, as reflected in national and international targets. For example, Saudi Arabia has outlined a strategy to use 23% of concentrated solar power (CSP) and 39% of photovoltaic (PV) energy in desalination plants by 2030 (Ghaffour et al., 2015). Similarly, the UAE, through its renewable energy company Masdar, established the Global Clean Water Desalination Alliance "H_20 minus CO_2" in 2015, as part of the Lima Paris Action Plan at COP21. The alliance set goals to increasingly reduce CO_2 emissions in desalination, aiming for a clean energy supply of 10% for operational plants by 2020, increasing to 20% for new plants by 2025, 40% by 2030, 60% by 2035 and 80% for new plants constructed after 2035.

Closely associated with energy efficiency research, 'Cost-Benefit Analysis' emerged as the third most frequent research theme in the review and it has remained constant over the years. These studies primarily focused on techno-economic analyses and feasibility assessments, covering topics ranging from the integration of renewable energy with various desalination technologies, to the comparative evaluation of concentrated solar power costs. The prominence of these two themes, alongside the shift in both research focus and industrial application from thermal evaporation technologies to membrane technologies, reflects the broader evolution towards more efficient and cost-effective approaches in desalination.

Beyond the significant focus on energy efficiency technologies and cost evaluations, the logistic, socio-economic and environmental dimensions of desalination have also received substantial attention. Ranking second among research themes, 'Institutional, Regulatory & Policy Concerns' signals to the complexity of water provision and management in the region. This body of literature addressed a broad spectrum of topics, including operational and managerial aspects, site selection considerations, environmental impacts, public-private partnerships, water pricing, institutional frameworks, multi-criteria decision analysis, transboundary water issues, the water-energy-food nexus, carbon footprint and life cycle assessments. The prominence of this theme highlights the critical need for robust policies and management systems as well as the growing recognition of the need to investigate and mitigate the environmental impacts associated with desalination.

Aside from these three major themes, the remaining ten research areas constituted a smaller proportion of the overall research output. Notably, themes with fewer than 100 publications included ‘Intake Improvements’, ‘Monitoring Improvements’, ‘Distribution System Integration’, ‘Anthropogenic Effects on Desalination’, ‘Brine Disposal Alternatives’ and ‘Pretreatment and Anti-Fouling Technologies’. Future research should prioritize these understudied themes, with particular emphasis on brine disposal alternatives, given the significant environmental impacts of brines on marine ecosystems (Ahmad & Baddour, 2014; Omerspahic et al., 2022). Shifting the focus to the technologies associated with these themes, it becomes evident that the region has experienced an evolution in the types of technologies being researched and deployed.

4.2 Desalination Technologies

Although a wide range of desalination technologies were identified in the 1,899 publications analyzed from the Middle East, much of the earlier research predominantly focused on traditional 'Thermal – Evaporation' methods, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). However, a notable shift has occurred since the late 1990s when desalination research has increasingly moved away from fuel-intensive thermal technologies towards more energy-efficient and environmentally sustainable 'Non-thermal – Membrane Technologies' such as Reverse Osmosis (RO), Forward Osmosis (FO) and Membrane Distillation (MD). Specifically, our data suggests that research on membrane technologies surpassed that of thermal desalination for water production by the early 2000s. Finally, while it remains unclear whether research trends have influenced industry practices or vice versa, the transition from thermal to membrane technologies in the research realm closely aligns with shifts observed in industrial desalination production. The drivers behind the shift towards membrane technologies are multifaceted but are primarily due to their higher efficiency, lower emissions and compatibility with renewable energy sources, which facilitate the decoupling of desalination processes from traditional energy sources (González et al., 2017). This shift reflects mounting environmental concerns and energy constraints in the region. Historically, thermal evaporation technologies were favored in the Middle East due to the availability of relatively inexpensive fossil fuel-derived energy, the ability to co-generate water and electricity by utilizing excess heat and the higher efficiency in desalting seawater (Fig. 6C) (Moossa et al., 2022). However, advances in membrane technology and pretreatment processes, coupled with their lower environmental impact and the decarbonization of the industry, have rendered membrane technologies more economically and politically viable for today's market (Moossa et al., 2022; Feria-Díaz et al., 2021). For example, the modular nature of RO allows for easier capacity expansion, integration with other technologies like FO to reduce fouling and improved compatibility with renewable energy sources (Obaid Sharif, 2016). Indeed, ongoing efforts to improve desalination sustainability are exploring the integration of renewable energy options with different desalination technologies. Studies indicate that thermal desalination technologies are better suited to solar thermal power, while Reverse Osmosis (RO) and Electrodialysis (ED) are more compatible with photovoltaic and concentrated solar power systems (Ghermandi & Messalem, 2009). This transition toward sustainable practices is beginning to see practical application in large-scale water desalination projects, exemplified by the first large-scale solar-powered desalination plant near Al Khafji City in Saudi Arabia and the solar-powered RO plant at Al Taweelah in Abu Dhabi, UAE (Al-Buraiki et al., 2024)

A notable portion of desalination research has focused on 'Renewable – Direct Solar' desalination technologies, such as Solar Stills and Humidification-Dehumidification (HDH) systems, particularly in the last decade. This strong regional interest in coupling desalination with solar thermal energy reflects the Middle East's abundant solar radiation as well as the ongoing efforts to enhance desalination sustainability (Ahmed et al., 2019; Feria-Díaz et al., 2021). However, Solar Stills and other small-scale technologies remain predominantly used to supply fresh water to villages and remote areas, particularly in Egypt and Iran, offering decentralized solutions to water scarcity (Ayoub & Alward, 1996; Yusof et al., 2022).

Only a small proportion of papers have explored 'Multiple and Hybrid' and 'Emerging' technologies, with these advancements not yet reflected in water production data, indicating that these new systems may still be in their early stages of development. However, several scaled-up projects suggest that hybrid systems may offer a promising solution to overcome existing barriers, such as RO combined with emerging technologies like FO (Feria-Díaz et al., 2021; Wang et al., 2018), or RO hybridization with thermal technologies. Such hybridization has already found industrial application in the Middle East, including the Al-Fujairah-2 plant utilizing MED-TVC-RO technologies in the UAE and the Ras Al-Khair plant employing MSF-RO hybridization in Saudi Arabia (Feria-Díaz et al., 2021). Although emerging technologies, such as Membrane Distillation, Capacitive Deionization and Electrodialysis, have been tested in pilot plants, further integration into large-scale applications is needed (Ahmed et al., 2021), as well as more research and development to enable low-cost mass production (Bundschuh et al., 2021; Ghaffour et al., 2015). Notably, Oman's installation of the world's first FO plant demonstrates the region's growing interest in pioneering emerging desalination technologies (Awad et al., 2019).

4.3 Authorship Trends

The exponential increase in scholarly desalination publications in the Middle East since the early 2000s underscores the importance of understanding the role of 'local' versus 'external' researchers in leading and producing knowledge. Such analyses can be particularly valuable in documenting the level of regional interest and involvement in this field, which is of critical interest for regional populations from a water security perspective. This review revealed that most desalination research across these 17 countries/nations was consistently conducted by first-authors based in higher educational institutions or research centers within the region at the time of publication. Since the 1980s, local institutions have published more than 80% of desalination research, reaffirming the high priority placed on desalination research as a vehicle for aiding economic development and ensuring water security. The prevalence of desalination research in the Middle East starkly contrasts with trends in other fields that still contend with ‘parachute science’— a practice where scientists from the Global North conduct research, collect data and/or export samples from the Global South (Odeny & Bosurgi, 2022). For example, in some areas of research, over 50% of literature produced in Gulf Cooperation Council member states has been authored by researchers based outside the region, a pattern argued to hinder the development of long-term, large-scale collaborative and multinational research initiatives (Al-Gergawi et al., 2024; Vaughan & Burt, 2016; Friis & Burt, 2020). However, our findings here suggest that ‘parachute science’ is limited in desalination research in the Middle East, where output is heavily driven by scientists and engineers who are based within the region.

A deeper analysis of first-author regions revealed a pattern where ‘local’ scientists and funds were more frequently associated with addressing country-specific desalination concerns (Table S4-5), while ‘international’ authors appeared more inclined to focus on pan-regional or global topics (Table S6). For example, first-author scientists based in ‘local’ institutions, such as Egyptian-based first-author Kabeel et al. (2023) enacted a solar-powered hybrid desalination system experiment using an evaporative humidification tower in El-Mahalla El-Kubra, near the Nile delta, while Qatar-based Yasseen & Al-Thani (2022) presented perspectives on endophytes and halophytes to remediate industrial wastewater and saline soils, tailored to national conditions. In contrast, first-authors working in ‘external’ institutions were more engaged in producing pan-regional reviews, assessing comparative studies and addressing transboundary issues. For example, Rusteberg et al. (2022) from the University of Göttingen, Germany, evaluated transboundary water transfer issues related to seawater desalination across the Middle East, while Chenoweth & Al-Masri (2022) from the University of Surrey, UK, discussed the cumulative effects of large-scale desalination on the salinity of semi-enclosed seas, including the Red Sea and the Gulf of Suez.

Approximately 30% of authors situated in European and North American institutions worked on issues related to 'multiple' countries, including those outside the Middle East (e.g., Siddiqi & Anadon, 2011; Palenzuela et al., 2015; Todd, 2017; Nayar et al., 2019), compared to only 7% of authors based in Middle Eastern institutions (e.g., Darwish, 2014; Saleh & Mezher, 2021; Fouladi et al., 2021), perhaps suggesting that local research is driven by priorities at the national rather than region-wide scale. Nevertheless, the process and outcomes of research production often occur collaboratively between authors from various regions, disciplines and institutions, a nuance that is more challenging to capture with the data gathered in this review. Indeed, the global review on desalination literature by Zapata-Sierra et al. (2021) emphasizes the importance of considering collaborative practices as most authors choose to cooperate with those outside their country. This trend may indicate country-level specializations in research or competition over funding and grants. Future studies should expand this analysis by exploring scientific collaborations both inter-regionally and intra-regionally, as well as by considering author nationality in addition to institution affiliation, which may be particularly important in regional nations with large resident expatriate populations, which raises questions about long-term knowledge retention.

4.5 Scientific Productivity and Desalination Production: A Statistical Analysis

The analyses in this study revealed a strong relationship between desalination research and desalinated water production, particularly in countries with high GDPs. In contrast, water stress levels and population size were not significantly related to either desalination research or freshwater production. These findings indicate that affluent nations may be better positioned to make the substantial investments required for the research, development, installation and maintenance of desalination infrastructure. Additionally, it may also imply that a higher GDP can be driven by the availability of desalinated water, as the expansion of desalination capacity contributes to greater water security, and thus, a more prosperous economy.

When accounting for population size, the Gulf States exhibit some of the highest per capita rates of desalinated water production in the Middle East, reflecting significant government efforts to ensure water availability and the high standard of living in these nations. For instance, Saudi Arabia was shown to be the most prolific producer of desalination research and freshwater production, with a similar trend observed in smaller Gulf States such as the UAE, Qatar, Kuwait and Bahrain. Despite very limited natural water availability, these countries have heavily subsidized water production, resulting in some of the highest per capita water consumption rates globally (Sherif et al., 2023), which, consequently, further increases the demand for desalination. Implementing more effective water policies and management practices could not only improve water supply, but also help curb water demand, especially considering predicted population growth.

4.6 Global Comparisons and Future Directions on Middle East Desalination Research

Despite a population of just over 40.3 million—representing less than 1% of the global population—the Middle East produces 46% of the world’s desalinated water. This disparity reflects the region’s high aridity and limited freshwater resources, which make desalinated water essential for maintaining living standards. However, despite accounting for nearly half of global desalination production, the 1,899 publications analyzed in this study represent only a small fraction of global desalination research. For instance, based on *SCOPUS* raw search results for ‘desalination’ (i.e., without manual filtering for eligibility), Middle Eastern publications constitute just 6.7% of global literature (2,718 out of 40,545), with the majority produced by China, the USA and India—the three most populous nations of the world (Zapata-Sierra et al., 2021). Thus, while the region has seen substantial growth in research and technological advancements, there remains significant potential for expansion, particularly around policies and technologies specific to the regional environmental context of the Middle East.

Given the high economic costs associated with desalination and the disproportionate risks posed by limited water availability to countries with constrained financial resources, future research should prioritize making desalination technologies more efficient and accessible for low- and middle-income nations. Specifically, due to the high solar irradiation in the Middle East, researchers should further investigate the potential of utilizing increasingly affordable renewable energies (such as photovoltaic) and direct solar thermal technologies to enhance water production in lower-income countries such as Palestine, Iraq and Yemen. Additionally, targeted research should investigate solutions for off-grid and rural communities, where decentralized water provision systems, such as solar stills, remain crucial (Al-Addous et al., 2024; Salloom et al., 2022; Al-Fakih & Al-Khudafi, 2014).

The integration of renewable energy sources and emerging desalination technologies into conventional practices aligns with ongoing efforts to decarbonize the industry. However, while pilot studies and demonstration plants have shown the benefit of such integrations and hybridizations—particularly in terms of energy efficiency and emission reduction (Feria-Díaz et al., 2021)—most projects have yet to scale up to widespread industrial implementation. Therefore, expanding research and development efforts will be crucial to bridge this gap and ensure a more sustainable desalination sector.

Finally, as the Middle East generates nearly half of the world’s brine effluent (Jones et al., 2019), more research into brine disposal alternatives is urgently needed. Specifically, greater emphasis must be placed on mitigating the effects of brine discharge on coastal marine ecosystems and developing methods to reduce or repurpose brine, aiming to achieve zero liquid discharge (Omerspahic et al., 2022). This issue is particularly pressing in a region where desalination activities are projected to double in many countries by 2030, and where the basin-wide impacts of brine discharges, particularly in semi-landlocked systems such as the Arabian/Persian Gulf and the Red Sea, remain contentious (Paparella et al., 2022). Furthermore, as only a few studies have specifically investigated the impact of brine discharge on organisms and coastal ecosystems in the Middle East, expanded research in this research area is needed to better inform policy-makers and achieve sustainable management practices.

3. Conclusion

As global water stress intensifies, desalination has become a vital alternative to conventional water sources, particularly in arid and semi-arid regions like the Middle East. This systematic review highlights the Middle East's dual role as a global leader in desalination production and an increasingly significant contributor to desalination research. Over the past decade, the region has experienced exponential growth in research output, with 83% of publications produced since 2013. Notably, the majority of these contributions are authored by researchers affiliated with Middle Eastern institutions, underscoring the importance of desalination in addressing acute water scarcity and its prioritization as a critical regional research focus.

Our findings reveal a strong alignment between research trends and industrial practices, particularly in the transition from thermal to membrane technologies and the integration of renewable energy sources. Energy efficiency, cost-benefit analyses and institutional, regulatory and policy concerns have emerged as the three dominant research themes in the region, underscoring the importance of reducing desalination costs and their critical role in national water security strategies. However, to ensure long-term water security and environmental sustainability, greater research attention is needed on other regionally relevant topics, including brine disposal alternatives, direct solar desalination and the large-scale adoption of hybrid systems and emerging technologies.

Finally, by focusing on the Middle East—a region uniquely poised to influence global desalination trends—our paper provides actionable insights for researchers, policymakers and industry leaders. The findings emphasize desalination's pivotal role in addressing present and future water security challenges, highlighting the necessity of targeted innovation and cross-sector collaboration to ensure a sustainable future.

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Authors contribution

D.D. designed the study with inputs from M.A.M., A.A.G. and J.A.B. Data were collected by D.D., M.A.M. and A.AG, while D.D. ran the analysis. D.D., M.A.M. and A.A.G. drafted the manuscript with comments and revisions from J.A.B. Data Availability Statement

Data available on request from the authors.

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Supplementary materials - Evolution of desalination research and water production in the Middle East: a five-decade perspective

Table S1 List of countries and grouping used across the study.

Africa	Algeria, Angola, Botswana, Cabo Verde, Chad, Comoros, Democratic Republic of the Congo, Equatorial Guinea, Ethiopia, Gabon, Ghana, Guinea, Kenya, Libya, Madagascar, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Nigeria, Republic of Congo, Saint Helena, Senegal, Seychelles, Sierra Leone, South Africa, South Sudan, Tanzania, Tunisia, Zambia, Zimbabwe.
Europe & Central Asia	Afghanistan, Albania, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Georgia, Germany, Gibraltar, Greece, Guernsey (UK), Hungary, Ireland, Italy, Jersey (UK), Kazakhstan, Latvia, Lebanon, Liechtenstein, Lithuania, Luxembourg, Malta, Moldova, Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Syria, Tajikistan, Turkey, Turkmenistan, Ukraine, United Kingdom, Uzbekistan.
Latin America & Caribbean	Anguilla, Antarctica, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia, Bonaire, Sint Eustatius and Saba, Brazil, British Virgin Islands, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Barthelemy, Saint Lucia, Saint Martin, Saint Vincent and the Grenadines, Sint Maarten, Suriname, Trinidad and Tobago, Turks and Caicos Islands, U.S. Virgin Islands, Uruguay, Venezuela.
Middle East	Bahrain, Egypt, Eritrea, Iran, Iraq, Israel, Jordan, Kuwait, Oman, Palestine, Qatar, Djibouti, Saudi Arabia (KSA), Somalia, Sudan, United Arab Emirates, Yemen.
North America	Bermuda, Canada, United States.
South-East Asia	Australia, Bangladesh, Brunei, China, Cook Islands, Fiji, French Polynesia, Guam, Hong Kong, India, Indonesia, Japan, Kiribati, Malaysia, Maldives, Marshall Islands, Myanmar, Nauru, New Zealand, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Philippines, Singapore, Solomon Islands, South Korea, Sri Lanka, Taiwan, Thailand, Tonga, United States Minor Outlying Islands, Vanuatu, Vietnam.

Table S2 Inclusion and exclusion criteria

	Inclusion Criteria	**Exclusion Criteria**
Study topic	Any publication on water desalination.	Publications not on water desalination (e.g., crude oil desalination).
Study type	Peer-reviewed publications (including conference papers and books when the full article was available for screening).	Non-peer-reviewed publications (e.g. reports, newspaper articles, trade journals) and retracted papers. Conference proceedings and books without the full article being available for screening.
Study geographical scope	Publications with territorial waters situated in the Middle East (i.e., any of the 17 demarcated countries sharing access to the Arabian/Persian Gulf, Oman Sea, Arabian Sea, and Gulf of Aqaba-Red Sea).	Publications outside the Middle East or from countries without access to the Arabian/Persian Gulf, Oman Sea, Arabian Sea, and Gulf of Aqaba-Red Sea.
Study time frame	December 31st, 2022.	Publications produced on or before December 31st, 2022.
Study database	*SCOPUS.*	Publications unavailable on *SCOPUS.*

Table S3 Research theme details (adapted from the US Bureau of Reclamation, 2014). Compared to the original framework, our table offers a consolidated and condensed list of research areas. International and domestic references were merged, duplicates removed, and region-specific criteria added.

Research Topic	Criteria
Energy Efficiency Technologies	➢ Investigate renewable power coupling to the desalination treatment process (e.g., wave energy). ➢ Determine how to achieve energy sustainability for desalination by minimizing energy consumption through investment in energy-efficient pumps and other equipment, purchasing renewable energy credits that offset the greenhouse gas loading of the facility's electricity and investing in greenhouse gas-reducing projects, from new renewable energy projects to carbon storage projects. ➢ Determine any synergistic effects caused by combining desalination's high salinity discharge with the high temperatures and dead biomass in power plant discharge. ➢ Evaluate energy price risk, including year-to-year variation and trends over time, in the revenue requirement of water utilities that invest in or purchase water from ocean desalination. ➢ Improve promising low-energy technologies (i.e., capacitive deionization) and alternative energy sources (i.e., wind and solar). ➢ Recover energy from reverse osmosis processes used for desalination. ➢ Use new technology (nanotechnology, energy efficient pumps, alternative energy sources, use of waste heat) to reduce the costs of operating and maintaining desalination processes and to reduce carbon footprint. ➢ Evaluate the co-location of steam electric power plants or large municipal wastewater treatment plants to reduce energy, capital and operational costs. ➢ Develop a statewide plan for water-energy resource planning to assist local and regional shareholders with a framework for coordination. ➢ Develop a mechanism for enhanced cooperation between water utilities and power companies to make existing and future desalination plants more cost-competitive. ➢ Model current oxidative conditioning of water to develop alternative pretreatments for conditioning seawater. ➢ Reduce or eliminate fouling of existing membrane systems in order to operate at a higher throughput. ➢ Facilitate operational adjustments at the pretreatment process that enable membrane operations and performance adjustments. ➢ Evaluate pre-heating using waste heat or renewable energy and the use of lower-pressure membranes. ➢ Investigate the direct use of renewable energy via kinetic, electrical, or thermal means. ➢ Couple water production with renewable energy. ➢ Develop solar ponds for energy and concentrate management. ➢ Develop solar poly vinyl-reverse osmosis systems. ➢ Develop energy recovery in RO processes. ➢ Reduce energy consumption and support the use of cheaper alternative energy sources. ➢ Expand the application of renewable energy sources for desalination. ➢ Support research and the development of more energy-efficient desalination technologies. ➢ Develop a new technology for high-recovery, low-energy desalination of brackish water by a new single-stage method without any loss of brine energy. ➢ Investigate the feasibility of desalting using renewable energy. ➢ Develop an optimal, economic, and efficient hybrid system that feeds the electric needs of a small-scale brackish reverse osmosis desalination unit. ➢ Improve the efficiency of solar stills as a new water production method for particularly rural populations. ➢ Design an integrated desalination with a small modular reactor that relies on thermal energy compatible with existing fossil fuel-powered desalination plants.

	➢ Optimize a photovoltaic-wind grid-connected system to power a reverse osmosis desalination plant, focusing on minimizing life cycle cost, reducing greenhouse gas emissions, and maximizing the grid contribution share. ➢ Investigate a solar-powered hybrid desalination system and highlight its operational compatibility between humidification-dehumidification and solar energy. ➢ Design and optimize a stand-alone hybrid renewable energy system, incorporating photovoltaic panels, wind turbines, batteries, and a diesel generator, with the objective of minimizing total life cycle cost, considering environmental impacts on human health and ecosystems, while maximizing system reliability. ➢ Explores energy hubs to optimize power generation and consumption, specifically focusing on integrating seawater desalination units, electric vehicles, and hydrogen energy to enhance flexibility and environmental potential in a cost-effective manner. ➢ Analyze and model a combined energy system that integrates concentrated solar power, steam Rankine cycle, Brayton cycle, organic Rankine cycle, reverse osmosis unit, and a thermoelectric generator, aiming to optimize thermodynamic performance and economic feasibility through cost minimization and exergy efficiency maximization. ➢ Test the performance of a solar desalination system using chemical dye-dosed water. ➢ Improve domestic hot water production and drinking water generation using solar stills, where incorporating copper oxide nanoparticles in the phase change material enhances its thermal characteristics and boosts system efficiency. ➢ Integrate large-scale renewable energy harvesting systems, such as solar and wind power, with energy storage technologies like seawater pumped storage hydropower. ➢ Comparatively assess electricity and water production using concentrating solar power and desalination plants. ➢ Enact an exergy analysis of desalination plants and ultrapure water units. ➢ Integrate the Allam cycle and Multi-Effect Distillation-Thermal Vapor Compression desalination system to reduce carbon dioxide emissions and simultaneously produce fresh water and power. ➢ Improve desalination pipeline systems utilizing the temperature difference under sub-atmospheric pressure. ➢ Investigate the optimal size of grid connections for hybrid PV, generator, and battery systems based on machine learning predictions of CO2 emission and electricity consumption.
Institutional, Regulatory and Policy Concerns	➢ Establish a program by which new membranes, membrane treatment-related products, and alternative desalination technologies are independently and comparatively tested under the conditions and constraints relevant to arid climates. ➢ Document regulatory permitting issues associated with seawater desalination. ➢ Establish a combined basic and applied research program to improve efficiency and decrease the cost of capacitive deionization. ➢ Assess the environmental impacts of desalination intake and concentrate management approaches. ➢ Analyze the human impacts of boron to expedite water-quality guidance for desalination process design. ➢ Address critical gaps in understanding the impacts of human exposure to constituents in reclaimed water. ➢ Assess the potential impacts of environmental applications of reclaimed water in sensitive ecological communities. ➢ Examine the public acceptability of multiple engineered barriers compared with environmental buffers for potable reuse.

	➢ Develop a better understanding of the formation of hazardous transformation products during water treatment for reuse and ways to minimize or remove them. ➢ Analyze the need for new reuse approaches and technology in future water management. ➢ Develop an education and public relations strategy to facilitate the implementation of desalination projects. ➢ Establish a national water policy to streamline regulations for the development of desalination. ➢ Establish a national advisory panel for developing water purification technologies to increase water supplies. ➢ Establish acceptable levels of boron, chloride, and sodium for plants common to households, yards and open spaces, as well as selected soil types and climates where seawater desalination is a viable candidate water source. ➢ Develop tools and standards to determine and assess the capacity of alternative water supply methods. ➢ Develop a portfolio approach to water supply planning to reflect desalination's different risks and benefits relative to alternative water supply options. ➢ Summarize regional case studies of policy modifications regarding water rights. ➢ Develop information necessary to achieve changes in regulatory requirements. ➢ Compile unsuccessful project case studies to allow barriers to be anticipated and potential policy changes to be implemented to streamline desalination implementation. ➢ Develop guidelines for desalination that address technical and institutional aspects of implementing desalination. ➢ Provide outreach and training for permitting processes and network water professionals. ➢ Study salinity tolerance of target-sensitive marine species. ➢ Map ocean shorelines for ‘near-shore’ outfall zones. ➢ Develop a surrogate-based method for assessment of algal toxin removal. ➢ Identify appropriate disposal or reuse of spent membrane cartridges. ➢ Identify policy developments to better understand energy-water interdependence. ➢ Develop a centralized understanding of national desalination deployment, performance and lessons learned. ➢ Develop a detailed understanding of marine species' salinity and toxin tolerance near plant outflows. ➢ Develop procedures for assessing the environmental impacts of desalination plant effluents. ➢ Promote the development and use of appropriate codes of practice and standards in materials, systems, operation and maintenance. ➢ Investigate the impact of meteorological factors on net freshwater consumption (NFWC) and develop a forecasting model for consumption rate. ➢ Potential impacts of brine discharge from desalination on the Arabian/Persian Gulf's salinity and the associated threats to marine ecosystems and water supply. ➢ Assess the potential impact of large-scale desalination on salinity levels, examining whether the projected growth of desalination activities by 2050 could result in elevated salinity levels in semi-enclosed seas. ➢ Evaluate social, economic and environmental factors to decide on desalination technology selection using an analytic hierarchy process. ➢ Consider social equity as a key factor in evaluating energy-water transition plans. ➢ Develop methodologies for assessing and ranking desalination processes based on their environmental performance.

	➢ Analyze the public aspects of desalination projects, including environmental impacts, mitigation and protection. ➢ Refine or advance desalination technology affecting regulatory parameters. ➢ Document equivalency of advanced wastewater treatment trains and processes for direct potable reuse. ➢ Develop standard terminology, messaging and communication materials to plan and implement direct potable reports. ➢ Identify the concerns about building a new supply source and improve public perception. ➢ Develop comprehensive public relations/public education programs. ➢ Evaluate source-water issues in relation to potential cost and fatal flow issues. ➢ Develop a better understanding of the ecological-economic impacts and provide a clearer and stronger framework for public review. ➢ Analyze the state of international relations and politics of water among countries. ➢ Exchange information on environmental issues associated with desalination. ➢ Revise regulatory bacteria and virus removal credits for reverse-osmosis membranes. ➢ Teach water resources managers about best management practices. ➢ Evaluate the effects of the operation of desalination plants on the environment. ➢ Coordinate and expedite permit reviews between various national and sub-national agencies to implement future desalination plants. ➢ Evaluate the possible risks to desalination facilities from oil spills by forecasting the oil spill travel time. ➢ Using Vensim as a modeling tool to choose the most effective water management activities to prevent water shortage. ➢ Examine the nexus of water footprint with energy and GDP to craft solutions for sustainable water usage. ➢ Promote the development and use of appropriate codes of practice and standards in materials, systems, operation and maintenance. ➢ Develop guidelines for a technology assessment model to analyze and identify water resources problems in project evaluation. ➢ Investigate amounts and sources of polycyclic aromatic hydrocarbons and their bioaccumulation factors in the zooplankton community. ➢ Enact a GIS-based multi-criteria evaluation decision rule for site selection of desalination plants. ➢ Examine the geographical preference for solar still installation based on technical, energy and economic criteria using an analytical hierarchy process. ➢ Model aquifer storage and recovery. ➢ Establish a conceptual approach for developing alternative water strategies based on seawater desalination and water transfer. ➢ Propose energy and air quality management recommendations based on generated emission reports. ➢ Significance of effective plant design and management of desalination plant outfalls in mitigating ecological impacts, emphasizing the necessity for careful consideration and implementation to ensure the manageable consequences of large-scale desalination operations. ➢ Develop methodologies for selecting brine discharge positions in slow-flushing zones to mitigate salt buildup and minimize environmental impacts. ➢ Examine the stability of the current salinity state in the Arabian/Persian Gulf and its response to perturbations from seawater desalination.

	➢ Develop a model using two techniques, fuzzy cognitive mapping and agent-based modelling, to compare the impacts of different water scarcity policy options on overall groundwater usage.
Treatment Improvements	➢ Explore outside-the-box innovative desalting solutions. ➢ Develop alternative technologies that desalinate and purify water to take advantage of non-traditional methods. ➢ Develop thermal technologies. ➢ Develop new concepts for non-traditional desalination. ➢ Conduct combined basic and applied research on the potential of incorporating novel membrane functionalities such as electromagnetic membranes, biomimetic membranes, and ion-specific electrodialysis membranes. ➢ Evaluate the impacts of treatment train and process operation modifications to enhance the performance and reliability of secondary, tertiary and advanced treatment systems. ➢ Evaluate new and alternative integrated technologies for optimizing seawater desalination plant design and operating concepts. ➢ Evaluate blending requirements for purified water. ➢ Optimize treatment for cost savings in energy, maintenance, manpower and other plant operating costs. ➢ Improve membrane system performance. ➢ Improve existing desalination approaches to reduce primary energy use. ➢ Develop novel approaches or processes to desalinate water to reduce primary energy use. ➢ Develop a better understanding of pathogen removal efficiencies and performance variability in various unit processes and multi-barrier treatment and develop ways to optimize these processes. ➢ Improve membrane process technology. ➢ Improve the fundamental understanding of membrane science. ➢ Evaluate membrane bioreactor applications to reduce the costs and increase the efficiency of systems. ➢ Develop innovative membrane test bed for seawater desalination. ➢ Evaluate low-cost small-system desalination using evaporation. ➢ Demonstrate clathrate seawater desalination. ➢ Develop and test flexible-use systems for treating waters of significantly varying salinities. ➢ Expand scientific understanding of desalination processes. ➢ Improve the quality and suitability of treated water for reuse. ➢ Develop membrane technologies (technologies that desalinate and purify water by pushing it through a semi-permeable membrane that removes contaminants). ➢ Develop reuse/recycling technologies, which are often membrane or alternative technologies designed to handle increased contaminant loads due to their post-consumer application. ➢ Develop better designs for membrane modules that efficiently transport water to the membrane surface and waste salts away from it. ➢ Develop alternatives to spiral membrane systems. ➢ Improve low-temperature thermal desalination to increase affordability for small systems. ➢ Develop approaches that employ low-temperature distillation processes driven by waste heat sources to reduce the volume of RO concentrate and increase freshwater recovery.

	➢ Improve technologies for removing organic and biological contamination, as well as dissolved salts, that will allow for the substantial recycling of water and will reduce strain on limited resources in the face of increasing demand. ➢ Identify new techniques and evaluate existing alternatives for removing boron during seawater RO. ➢ Investigate the use of improved membranes, soluble salt control and system design improvements. Research additional secondary recovery strategies such as electro-deionization and selective adsorbents. ➢ Evaluate arrays, vessel configuration, variation in type(s) of membranes, etc. (e.g., staged feeding, modified arrays, varying type of membrane from front to back of system due to differential loadings). ➢ Develop hybrid systems that can treat very difficult brackish source waters. ➢ Demonstrate the scalability of membrane distillation. ➢ Develop a forward osmosis desalination process that can operate at a lower cost and water recovery than RO. ➢ Investigate biomimetic membrane filtration in synthetic systems. ➢ Improve membrane productivity, rejection, selectivity and manufacturing reproducibility. ➢ Improve membrane materials to reduce operating pressure while maintaining or increasing flux rates and maintaining ion rejection. ➢ Optimize contaminant removal without the need for second-pass RO. ➢ Optimize operations of RO desalting for plant simplification. ➢ Develop novel technologies, including those for direct agricultural and industrial use. ➢ Develop low-maintenance, reliable evaporative technologies using waste heat or renewable energy. ➢ Pilot real-world situations and breakthroughs near commercial desalination technology. ➢ Design reliable and robust small-scale systems. ➢ Design and manufacture solar stills. ➢ Apply reflection reduction solution to the glass of solar desalination units. ➢ Provide continuous improvement in material enhancement for solar desalination units. ➢ Manufacture of stand-alone small desalination units (1-20 $m^3 d^{-1}$). ➢ Develop an integrated complex to produce water (solar stills), electricity (wind, solar, biomass), food (greenhouses self-sufficient in irrigating water, rabbit, sheep and birds breeding) and salts (chemical salts and nutrients). ➢ Enhance evaporation through a multistage condensation evaporation cycle. ➢ Study the biology of salty water, including understanding environmental impacts and using bacteria for beneficial treatment. ➢ Develop ionization of salty water for irrigation. ➢ Develop performance improvements for thermal desalination processes. ➢ Improve operation, efficiency and reliability of the many conventional desalination plants currently in operation. ➢ Improve desalination processes for reducing and/or disposing of effluents and include the assessment of the composition of desalination plant effluents. ➢ Develop hybrid desalination processes to reduce capital, operation, and maintenance costs. ➢ Identify treatment for acid mine drainage and other saline mine waters. ➢ Develop treatment for mining and industrial process effluents. ➢ Prototype efficiency and the clean water production rate. ➢ Explore the optimization of membrane element performance characteristics under hot climate conditions. ➢ Low-cost membrane development using cellulose triacetate-based membranes from palm fronds.

	➢ Modelling the interaction of ions and water molecules with nanotubes (CNTs) and ionized carbon nanotubes (I±-CNTs) for water purification and ion rejection. ➢ Enact brackish water treatment by integrating mesoporous γ-Al2O3NPs with thin-film nanofiltration membranes. ➢ Conduct electrodialysis reversal performance for rejected brine treatment. ➢ Utilize hollow copper circular fins and glass wool insulation on the productivity and efficiency of solar stills. ➢ Improve the treatment process of desalination by utilizing a novel design of a helical humidifier and a multi-section solar distiller. ➢ Design and fabricate a three-dimensional open architecture solar evaporator incorporating vertically aligned mass transfer bridges to enable efficient water evaporation, salt prevention, conductive heat recovery and stable freshwater production from diverse brines. ➢ Compare the performance of single-slope solar stills using plain brackish water versus chemical dye-dosed water to enhance freshwater production, examining the impact of chemical dyes on distillation efficiency and output. ➢ Test the viability of desalinating oil field-produced water using a direct contact membrane distillation system. ➢ Propose an ultrapure water unit coupled to a reverse osmosis desalination plant. ➢ Design a small thermal desalination unit for use in refugee camps or emergency situations. ➢ Employ a specific treatment method, such as the solar hybrid adsorption desalination-cooling system using silica gel-water to achieve desalination and cooling.
Pre-Treatment and Anti-fouling Technologies	➢ Evaluate the implementation and cost of various pre-treatment strategies to allow greater RO water recovery before the onset of scaling. ➢ Reduce RO membrane fouling through feed water pretreatment and coupling of RO systems to ion exchange processes or nanofiltration. Other approaches include membrane improvements and mechanical or chemical ways to inhibit scaling. ➢ Evaluate the relative efficacy of the various commercially available anti-scalants and identify a standard testing protocol by which these and future products in the market can be comparatively rated. ➢ Evaluate feedwater treatment processes and strategies. ➢ Explore mechanisms to decrease membrane fouling. ➢ Improve pretreatment and anti-fouling technologies. ➢ Develop new membrane materials that work efficiently at high temperatures. ➢ Improve pretreatment for membrane desalination. ➢ Develop better methods of preventing membrane fouling. ➢ Model current oxidative conditioning of water to develop alternative pretreatments for conditioning seawater. ➢ Develop process and feedback control mechanisms that lead to design guidelines for pretreatment systems. ➢ Identify naturally occurring geo- and bio-polymers in seawater. ➢ Identify organic fouling control mechanisms and develop real-time sensing tools. ➢ Reduce or eliminate fouling for existing membrane systems to operate at a higher throughput. ➢ Facilitate operational adjustments at the pretreatment phase to enable membrane operations/performance adjustments. ➢ Determine the optimal use of chemicals. ➢ Identify and research specific issues for pre-treatment in rural and remote areas relating to seasonal and location variability in feedwater composition.

	➢ Improve anti-fouling technologies and membranes and oxidant-resistant membranes. ➢ Investigate microbial and chemical compositional changes in RO membrane fouling layers. ➢ Investigate the effect of hybrid salts precipitation-nanofiltration process on the scale deposits in thermal and membrane desalination processes. ➢ Investigate flux patterns and membrane fouling propensity in seawater forward osmosis. ➢ Investigate the effect of micro- and macro-organisms on the corrosive behavior of various alloys. ➢ Investigate the possibility of fouling and scaling on the membrane surface of hollow fibers and feed solution in treating produced and processed water. ➢ Model scale formation mechanisms in desalination processes. ➢ Develop process and feedback control mechanisms that lead to design guidelines for pretreatment systems.
Cost-Benefit Analysis	➢ Determine the economic and social benefits of drought-proof water supplies. ➢ Develop a delivery process to minimize costs and maximize performance. ➢ Identify, optimize and control the complexity and experience level required for several minor cost components for seawater desalination projects. ➢ Understand the relationship between finished-water quality specifications and plant design/cost. ➢ Develop a methodology to facilitate assessments of desalination options and total benefits. ➢ Explore ways to reduce associated energy consumption and operational costs. ➢ Quantify the non-monetized costs and benefits of potable and non-potable water reuse compared with other water supply sources to enhance water management decision-making. ➢ Determine the value of water for different water users. ➢ Develop approaches to lower the financial costs of desalination. ➢ Identify case study examples of alternative water supply evaluations that have been completed and used by decision-makers to prioritize and justify investments in new water supplies. ➢ Develop a documented process for using a normalized spreadsheet-based desalination cost model. ➢ Provide an inventory of capital, operational and maintenance costs for different qualities of product water for use by utilities and planners. ➢ Develop a total life cycle analysis and sustainability assessment of desalination against other water sources. ➢ Conduct techno-economic analysis/feasibility studies of sustainable energy plants according to location and/or compared to conventional energy usage. ➢ Map sustainable energy resources for the best desalination sites. ➢ Modify the replacement model to calculate the economic life and total cost in terms of net present value to evaluate a desalination plant's economic and financial lifetime. ➢ Assess the socio-economic and political feasibility of water imports to lessen dependence on desalination. ➢ Identify cost and energy-effective seawater membranes for use under hot climate conditions. ➢ Economic viability and potential cost-savings of implementing a solar chimney power plant system for water production compared to reverse osmosis technology.

	➢ Explore the cost-effectiveness of various energy system configurations by analyzing the impact of different diesel fuel prices, comparing seawater reverse osmosis desalination systems integrated with different combinations of photovoltaic panels, wind turbines, diesel generators and batteries. ➢ Analyze the techno-economic, environmental and energy dimensions and optimizations of integrated solar parabolic trough collector and multi-effect distillation systems with a combined cycle power plant. ➢ Explore the environmental, exergoeconomic and cost of water production analysis of implementing solar district heating and solar desalination. ➢ Examine the technical feasibility of hydro-powered reverse osmosis desalination systems, including the unit cost of brackish groundwater and seawater. ➢ Conduct an economic analysis of supplying rural wadi valleys with either desalinated seawater or treated wastewater conveyed via a managed aquifer recharge system.
Water Quality Concerns	➢ Investigate the benefits of targeting the quality of the output given the quality of the input water. ➢ Explore advanced wastewater treatment processes such as high-pressure membrane filtration and advanced oxidation to address trace organic contaminants persisting through conventional treatment processes. ➢ Remove nutrients and recover resources, including energy and nutrients. ➢ Remove chemical contaminants such as endocrine-disrupting compounds and pharmaceuticals. ➢ Pilot studies treating agricultural return flows containing elevated levels of total dissolved solids and selenium. ➢ Evaluate and test treatment approaches for problem contaminants. ➢ Develop and verify framework/model to describe and predict rejection of trace organic compounds. ➢ Study the survivability of regulated human pathogens in saline waters. ➢ Improve real-time monitoring and classification of potential foulants. ➢ Assess hazardous and/or toxicity of water quality from different sources for human consumption. ➢ Assess the mineral content of bottled and desalinated household drinking water. ➢ Compare the concentrations of inorganic chemicals in different domestic water types with World Organization limits for drinking water. ➢ Field-test condensation irrigation systems that combine desalination with subsurface irrigation by evaluating the system's effectiveness in producing drinking and irrigation water and assessing heat and moisture transfer in the soil. ➢ Establish a hydrodynamic model of brine disposal in artificial lagoons. ➢ Examine the effectiveness of solar distillation technology in reducing salinity and hardness from brackish groundwater. ➢ Identify suitable locations for managed aquifer recharge to replenish a coastal aquifer, addressing water supply challenges and ensuring water quality in the face of potential drought and plant malfunctions. ➢ Investigate household willingness to reuse treated greywater for non-drinking domestic purposes. ➢ Monitor inorganic and organic pollutants in desalinated water from thermal plants.

Brine Disposal Alternatives	➢ Investigate feasible strategies for and means of encouraging centralized ion exchange media regeneration vis-à-vis in-home regenerative water softeners to minimize water consumption and brine disposal impacts ➢ Evaluate brine/concentrate issues and options. ➢ Improve brine/concentrate management and disposal. ➢ Develop brine/concentrate management technologies. ➢ Investigate injecting rejected water into depleted oil and gas fields. ➢ Characterize benthic fauna in areas that will be affected by concentrate discharges. ➢ Model currents and tides to determine the impact on concentrate dispersion. ➢ Improve brine disposal and cost-effectiveness of various brine disposal and management technologies, such as zero liquid discharge and brine reuse potential. ➢ Evaluate hybrid techniques for zero-liquid discharge. ➢ Develop novel zero liquid discharge processes. ➢ Develop cost-effective approaches for concentrate management that minimize potential environmental impacts. ➢ Balance increasing potable water production and reducing the cost of the ultimate disposal of concentrate. ➢ Quantify the potential benefits and applicability of integrating the treatment of brackish water concentrate and seawater. ➢ Compile existing information on additives typical of desalination facility operations, including naturally derived additives, and identify knowledge gaps in our current understanding of additive fate, transport and risk. ➢ Develop a better understanding of brine/concentrate impacts on the environment and reevaluate the current methods used to determine these impacts. ➢ Develop a geomaterial liner that incorporates concentrate components to self-seal liners. ➢ Reduce land requirements for concentrate management by providing an additional treatment tool to maximize evaporation rates in evaporation ponds. ➢ Develop a better understanding of the impact of concentrates on wastewater treatment plant operations, particularly as the volume of these concentrates increases. ➢ Evaluate the ability to remove selective contaminants to produce saleable projects. ➢ Develop novel nano-materials that can rapidly and effectively remove silica from solutions. ➢ Develop an understanding of and a system design for minimizing antiscalants and biocides. ➢ Develop selective precipitation and purification methods for common RO concentrate salts and identify potential regional markets for beneficial reuse. ➢ Create new concentrate disposal options and improve public perception by applying concentrates in spa or environment/recreation improvements. ➢ Identify ways to mitigate adverse impacts of brine disposal. ➢ Develop an information and decision tree for characterization of desalination plant discharges. ➢ Characterize the toxicity impacts of desalination plant discharges. ➢ Develop standard methods for laboratory analysis of brine/concentrate. ➢ Develop, verify and certify salinity dispersion models tailored for seawater discharge. ➢ Develop a database of permitting practices for brackish concentrate disposal. ➢ Minimize and optimize produced waste based on value-added and beneficial use. ➢ Utilize energy efficiency in concentrate management such as waste heat, energy recovery, co-siting and evaporator technologies. ➢ Develop solar ponds for energy and concentrate management.

	➢ Improve secondary treatment of brine for salt production. ➢ Investigate desalination's technical and environmental feasibility and provide guidelines for establishing saline surface pans or lakes as regional facilities for brine disposal. ➢ Investigate the technical and financial feasibility of recovering useful and saleable products from desalination waste streams. ➢ Create a marine outfall design for environmental impact reduction.
Vegetation Use	➢ Develop and/or identify halophytes with commercial value that can be grown in lined facilities irrigated with RO brines. ➢ Develop a better understanding of contaminant attenuation in environmental buffers. ➢ Examine potential contributions from biotechnology and the biological sciences to produce potable water at useful scales. ➢ Evaluate the impacts of a typical brine stream on commercial agriculture and horticulture. ➢ Investigate integrated biological processes for salinity control. ➢ Preliminary evaluation of an on-site, low-energy, natural treatment of domestic wastewater using a constructed wetland. ➢ Investigate the utility of three algal species for desalination.
Distribution System Integration	➢ Develop the capability for case-specific, system-level evaluation of complete process schemes for desalination and brine management, including developing the necessary modelling tools and metrics. ➢ Determine the impacts of desalinated product water, which can be corrosive or damaging, on distribution systems. ➢ Develop design considerations for sizing engineered storage buffers. ➢ Investigate and develop guidelines for integrating desalinated seawater into existing drinking water distribution networks. ➢ Evaluate green infrastructure effectiveness and integration with water reuse and reclamation at the watershed scale. ➢ Optimize water stabilization for integration with existing infrastructure.
Monitoring Improvements	➢ Enhance monitoring techniques and methods for direct potable reuse. ➢ Develop protocols for sampling, testing, analysis and monitoring. ➢ Improve prevention and preparedness for bioterrorism. ➢ Strengthen waterborne disease surveillance, investigation methods, governmental response infrastructure, epidemiological research tools and capacity. ➢ Quantify the relationships between polymerase chain reaction detections and infectious organisms in intermediate and final stages samples. ➢ Develop improved techniques and data to consider hazardous events or system failures in risk assessment of water reuse. ➢ Identify better indicators and surrogates that can be used to monitor process performance in reuse scenarios and develop online real-time or near real-time monitoring techniques for their measurement. ➢ Establish a standard method for online nanofiltration and RO integrity testing. ➢ Substantially enhance the acceptability of desalinated water by developing quantitative guidelines linking post-treatment stabilization to water quality goals. ➢ Improve the emergency preparedness of wastewater treatment plants to deal with pandemics, new strains of viruses and bacteria or spill incidents.

	➢ Develop mitigation strategies for treatment plants after natural calamities.
Intake Improvements	➢ Evaluate feedwater intake technology and impacts. ➢ Study mixing zone turbulence entrainment. ➢ Improve thin-layer mixing models as part of far-field plume modelling. ➢ Research ecosystem impacts from water withdrawal and water intake structure. ➢ Develop improved intake methods at coastal facilities to minimize the impingement of larger organisms and entrainment of smaller ones. ➢ Assess information that can be used to examine intake options adequately. ➢ Develop a methodology for quantification of impingement and entrainment (I&E) of desalination plant intakes. ➢ Develop a methodology for determination of the biological significance of I&E. ➢ Develop a methodology for assigning I&E reduction credits to intake technologies. ➢ Develop a methodology for developing I&E mitigation. ➢ Develop a methodology for assigning pathogen removal credits to desalination intake wells. ➢ Optimize water intakes and outfalls. ➢ Establish management of entrainment of small marine organisms in plant intakes. ➢ Improve procedures for selecting appropriate intake and outfall systems based on the site conditions and development of new intake and out-fall systems. ➢ Transport modelling study for organic pollutants.
Anthropogenic Impacts on Desalination	➢ Assess how climate change and its concomitant consequences affect desalination plants (e.g., sea level rise in coastal zones). ➢ Discuss how oil and nuclear water spills affect desalination processes. ➢ Investigate the use of brackish groundwater and solar energy to mitigate the impacts of climate change on irrigation water shortage. ➢ Explore the effects of coastal urbanization and urban planning on desalination operations and processes.
Miscellaneous	➢ Assess the quantity and distribution of brackish water resources nationwide. ➢ Survey of existing brackish groundwater sources and water blending practices. ➢ Assess the conceptual feasibility for energy reduction, process productivity improvements, or environmental mitigation potential of offshore intakes and offshore desalination. ➢ Investigate the availability and use of brackish waters to meet future water needs for rural communities. ➢ Develop a methodology for performing sanitary surveys and applying drinking water standards to desalination projects. ➢ Characterize and map groundwater and seawater sources to explore those best fit for desalination technologies. ➢ Selection of groundwater sites for desalination by solar energy using GIS. ➢ Investigate the motion behavior of a novel floating desalination plant during towing operation. ➢ Two-dimensional numerical model of thermal discharge in coastal regions. ➢ Simulation of the impact of solar radiation intensity on the performance of economical solar water desalination still.

	➢ Evaluation of the hydro-chemical characteristics of groundwater and its suitability for desalination to produce potable water. ➢ Impact of water storage tank material on bacterial quality. ➢ Systematic documentation of corrosion data to reduce desalination costs. ➢ Environmental impacts of using desalinated water in concrete production within areas affected by freshwater scarcity. ➢ Worldwide research trends on desalination.

Table S4 Contribution of 'First Author Region' to the academic productivity of each 'Studied Country'.

Study Country	First Author Region	N studies	%
Bahrain		**43**	
	Middle East	32	74%
	Europe & Central Asia	7	16%
	South-East Asia	2	5%
	Latin America & Caribbean	1	2%
	North America	1	2%
Egypt		**222**	
	Middle East	192	86%
	Europe & Central Asia	25	11%
	North America	4	2%
	South-East Asia	1	0%
Iran		**196**	
	Middle East	174	89%
	Europe & Central Asia	9	5%
	South-East Asia	8	4%
	North America	5	3%

Iraq		**33**	
	Middle East	26	79%
	South-East Asia	4	12%
	Europe & Central Asia	2	6%
	North America	1	3%
Israel		**168**	
	Middle East	145	86%
	Europe & Central Asia	11	6%
	North America	11	6%
	South-East Asia	1	1%
Jordan		**16**	
	Middle East	12	75%
	Europe & Central Asia	3	19%
	South-East Asia	1	6%
Kuwait		**222**	
	Middle East	184	83%

	Europe & Central Asia	24	11%
	North America	9	4%
	South-East Asia	3	1%
	Africa	2	1%
Multiple		**214**	
	Middle East	104	49%
	Europe & Central Asia	60	28%
	North America	31	14%
	South-East Asia	16	7%
	Africa	2	1%
	Latin America & Caribbean	1	0%
Oman		**62**	
	Middle East	52	84%
	Europe & Central Asia	6	10%
	Africa	2	3%
	South-East Asia	2	3%
Other		**10**	

	Middle East	5	50%
	North America	3	30%
	Europe & Central Asia	1	10%
	South-East Asia	1	10%
Palestine		24	
	Middle East	17	71%
	Europe & Central Asia	7	29%
Qatar		**65**	
	Middle East	55	85%
	Europe & Central Asia	7	11%
	South-East Asia	2	3%
	North America	1	2%
Saudi Arabia		**36**	
	Middle East	292	80%
	Europe & Central Asia	26	7%
	North America	27	7%
	South-East Asia	19	5%

	Africa	1	0%
UAE		**166**	
	Middle East	118	71%
	Europe & Central Asia	28	17%
	North America	10	6%
	South-East Asia	10	6%

Table S5 Partition of research contribution of 'First Author Institute' to the research output of each 'Studied Country'.

	Studied Country													
First Author Institute	**Iran**	**UAE**	**Egypt**	**Israel**	**Kuwait**	**Multiple**	**Jordan**	**Saudi Arabia**	**Bahrain**	**Oman**	**Qatar**	**Iraq**	**Palestine**	**Grand Total**
Bahrain	–	–	–	–	–	3	–	–	30	–	–	–	–	33
Egypt	–	3	183	–	5	6	1	4	–	–	1	–	2	205
Iran	171	1	1	–	–	5	-	1	–	–	–	1	1	181
Iraq	–	–	–	–	–	1	-	-	–	–	–	25	–	26
Israel	–	–	–	145	–	20	-	-	–	–	–	–	3	168
Jordan	–	1	–	–	1	4	10	2	–	–	1	–	–	19
Kuwait	–	2	1	–	173	5	–	1	-	–	1	–	–	183
Oman	–	–	–	–	–	9	–	2	-	52	–	–	–	63
Palestine	–	–	–	–	–	–	–	–	–	–	–	–	11	11
Qatar	2	1	1	–	3	11	1	–	–	–	50	–	–	69
Saudi Arabia	1	–	5	–	-	21	–	279	1	–	1	–	–	308
UAE	–	110	1	–	2	19	–	3	1	–	1	–	–	137
Grand Total	174	118	192	145	184	104	12	292	32	52	55	26	17	1403
%	98%	93%	95%	100%	94%	–	83%	96%	94%	100%	91%	96%	65%	–

Table S6. Detailed data of Number of Publications, Desalination Capacity, GDP, Water Stress, and Population by Country

Country	Number. of Publications	Desalination capacity (M m3/d-1)	GDP (billion USD)	Water Stress (%)	Population (M)
Bahrain	33	1.2346	34.622	133.707	1701.583
Djibouti	1	0.0252	3.181	6.333	988.002
Egypt	220	2.1710	383.818	141.166	102334.403
Eritrea	0	0.0011	2.065	11.175	3546.427
Iran	192	1.4139	239.735	81.289	83992.953
Iraq	26	0.5634	180.924	79.514	40222.503
Israel	177	2.2777	413.267	110.085	8655.541
Jordan	19	0.2881	43.579	104.313	10203.140
Kuwait	189	3.6104	105.949	3850.5	4270.563
Oman	63	2.2710	75.909	116.714	5106.622
Palestine	11	0.0546	15.532	50.264	5101.416
Qatar	73	3.0493	144.411	431.034	2881.060
Saudi Arabia	319	16.9850	734.271	974.1666	34813.867
Somalia	0	0.0002	6.880	24.528	15893.219
Sudan	1	0.0446	27.035	118.656	43849.269
UAE	141	10.9430	349.473	1587.333	9890.400
Yemen	0	0.0729	21.606	169.762	29825.968