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National University of Trujillo, Peru

*CORRESPONDENCE
Daniele D'Agostino
✉ dagostino.daniele@outlook.com

†PRESENT ADDRESS
Daniele D'Agostino,
School of Life Sciences, University of Nottingham, Nottingham, United Kingdom

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

Daniele D'Agostino[1,2*†], Maryam Al-Memari[3] and John A. Burt[1,3,4,5]

[1]Water Research Center, NYU Abu Dhabi, Abu Dhabi, United Arab Emirates, [2]School of Life Sciences, University of Nottingham, Nottingham, United Kingdom, [3]Marine Biology Lab, NYU Abu Dhabi, Abu Dhabi, United Arab Emirates, [4]Center for Interacting Urban Networks (CITIES), NYU Abu Dhabi, Abu Dhabi, United Arab Emirates, [5]Mubadala Arabian Center for Climate and Environmental Sciences, NYU Abu Dhabi, Abu Dhabi, United Arab Emirates

Introduction: Rapid urbanization and groundwater depletion have entrenched reliance on desalination across the arid Middle East, which now accounts for ~46% of global capacity. Yet, the extent to which the region's research enterprise aligns with rapidly expanding industrial capacity has not been assessed comprehensively.
Methods: We conducted a PRISMA-based systematic review of SCOPUS records to 31 December 2022, identifying 1,899 publications (1972–2022). Scientometric analysis quantified temporal trends in publications, research themes, authorship geography and technological advancements. Desalination plant data (1950–2027) from Global Water Intelligence were used to derive national capacities. Associations between research, capacity and socio-economic or water-stress metrics were tested with correlation and linear models.
Results: Publications rose sharply after the early 2000s, with 83% published between 2013 and 2022. Dominant themes were energy efficiency (24%) and institutional/regulatory concerns (22%), followed by treatment improvements and cost–benefit analyses (~11% each). Authorship was primarily region-based (~80%), a stark contrast with other research fields. In 2022, regional capacity reached ~45 million $m^3 d^{-1}$ (Saudi Arabia 17; UAE 11), with ~60 million projected by 2027. GDP correlated strongly with publication volume ($r = 0.90$) and capacity ($r = 0.83$); publications and capacity were also correlated ($r = 0.74$), while population and water-stress metrics were not. Research focus shifted from thermal to membrane technologies, yet ~50% of regional capacity remains thermal versus >95% non-thermal globally.
Conclusions: These findings underscore the central role of desalination research and water production in regional water security and highlight the need to better align research priorities with operational realities and environmental safeguards through targeted innovation and cross-sector collaboration.

KEYWORDS

desalination, systematic review, research trends, Middle East, Arabia, water production, technological advancements, water-energy nexus

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 and 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; Calvin et al., 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, 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 and 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 and Zaidi, 2018). Today the Middle East houses just under half of the global desalination capacity (45.9%), each day producing 68 million cubic meters of desalinated water (Global Water Intelligence, 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.

Building on this context, it is necessary to examine the body of research that has guided desalination in the Middle East, a step that has not yet been undertaken systematically. Advances in the modern era of desalination would not have been possible without sustained research, which has been central to developing innovative solutions for water security, energy efficiency and environmental sustainability. Yet, no study has systematically reviewed desalination research across the Middle East while integrating water production data and socio-economic drivers. Such an approach is essential to provide a comprehensive view of how desalination has evolved, its current status and its central role in regional development. Previous reviews have offered valuable insights but have primarily relied on bibliometric analyses, which provide useful metrics yet limited explanatory depth. For example, Zapata-Sierra et al. (2021) and Chowdhury et al. (2024) respectively utilized *SCOPUS* and *Web of Science* to chart global desalination research, identifying leading countries, institutions, common keywords and research topics. However, neither study connected research to production or socio-economic drivers, nor did they provide substantial regional context. Zyoud and Fuchs-Hanusch (2015) provided a more focused analysis of desalination research in Arab nations, although their dataset ended in 2014 and excluded other key Middle Eastern countries, such as Iran and Israel. Some efforts have gone further, such as Jones et al. (2019), who combined bibliometric and production data to estimate global brine discharges, finding outputs nearly twice as high as previously estimated and identifying the Middle East as a major contributor, though their focus was confined to brine output rather than the broader research–production nexus. Similarly, regional reviews have typically been narrow in scope, focusing on specific topics such as renewable energy integration (Al-Karaghouli et al., 2009; Mahmoudi et al., 2023; Sayed et al., 2023), the water–energy nexus (Maftouh et al., 2022), or isolated countries and subregions, such as the Gulf Cooperation Council countries (Elsaie et al., 2023; Moossa et al., 2022). While valuable, these studies do not capture the full breadth of desalination research across the Middle East or connect scientific output with production trends and socio-economic factors.

To address this gap, the present study has three specific aims: (1) to conduct a systematic review to rigorously search, categorize, and comparatively analyze historical trends in desalination research across the 17 countries/nations bordering the Red Sea, the Gulf of Aqaba, the western Arabian Sea, the Sea of Oman, and the Arabian/Persian Gulf (collectively referred to here as the Middle East); (2) to investigate changes in desalinated water production volumes and technologies in the region using data from the Global Water Intelligence (Global Water Intelligence, 2022) database; and (3) to statistically examine the relationship between scientific publication output and water production together with metrics of economic performance, demography and water stress to better understand the association between research, industrial activity and the underpinning socio-economic factors.

By examining trends in desalination literature, such as publications by country, research themes and technological applications, and linking them with desalination production capacities and socio-economic drivers, this review provides a synoptic perspective on the evolution of desalination in the Middle East. Our findings not only highlight region-specific research gaps and misalignments between academic priorities and industrial needs, but also offer actionable insights to foster collaboration and innovation in addressing the region's escalating water crisis.

2 Methods

2.1 Trends in research productivity

To assess trends in water desalination research, we conducted a systematic literature review to identify relevant publications. The database search followed the PRISMA framework (Preferred Reporting Items for Systematic Reviews), comprising four stages: identification, screening, eligibility and inclusion (Moher et al., 2015) (Figure 1).

We 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 in 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 and regional desalination reviews such as Zyoud and Fuchs-Hanusch (2015) and Zapata-Sierra et al. (2021). The geographic scope was restricted to the 17 countries/nations bordering the Red Sea and the Gulf of Aqaba, the Arabian/Persian Gulf and the Western Arabian Sea (including the Sea of Oman to the Iran-Pakistan border and the Gulf of Aden to Puntland in northern Somalia) (Supplementary 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" OR "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

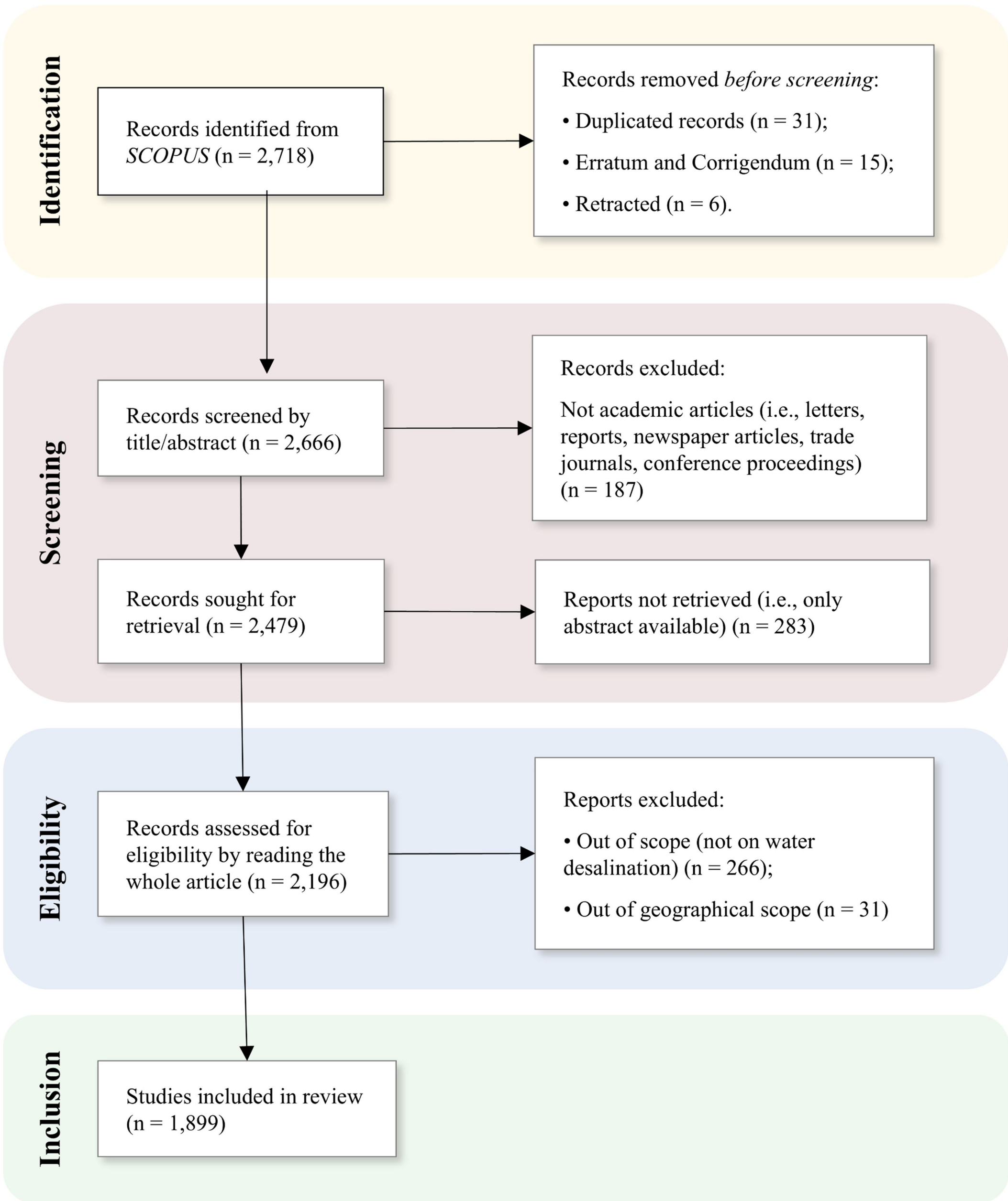

FIGURE 1
PRISMA diagram of the research process.

in Microsoft Excel, with duplicates, retractions, inaccessible and out-of-scope papers manually removed prior to analyses ('PRISMA process' below and Supplementary Table S2 'Exclusion rationale' for details). Each paper was independently assessed and screened by two different authors (MA-M and DD'A), with a third screener (JB) intervening in cases of disagreement.

During the first stage of the PRISMA process (identification), 2,718 publications were retrieved from SCOPUS. After removing duplicates ($n = 31$), errata and corrigenda ($n = 15$), and retracted papers ($n = 6$), 2,666 publications remained. Screening proceeded in two steps. First, titles and abstracts were reviewed to exclude non-academic records (e.g., letters, reports, newspaper articles, trade journals, conference proceedings), reducing the dataset to 2,479. Next, all remaining publications were sought for full-text retrieval and 283 records were excluded because the full text was unavailable. During the eligibility phase, the 2,196 retrievable publications were read in full, and articles not focused on water desalination ($n = 266$) or outside the defined geographic scope ($n = 31$) were removed. This process yielded a final set of 1,899 publications for inclusion in the review.

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 Supplementary 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 (2014) thematic framework for desalination research priorities (Supplementary 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 (Global Water Intelligence, 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

TABLE 1 Criteria for categorizing desalination publications into 13 research themes (see Supplementary 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.
Pretreatment 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 studies 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); Electrodialysis Reversal (EDR); Microfiltration/ Ultrafiltration/Nanofiltration (MF/UF/NF).
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 and 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.

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 and Central Asia; (3) Latin America and Caribbean; (4) Middle East; (5) North America; and (6) South East Asia (Supplementary 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 analyses

Metrics of economic performance (Gross Domestic Product [GDP], World Bank, 2023), demography (population size in millions of inhabitants, United Nations, 2022) and water stress (ratio of total freshwater withdrawn to total renewable freshwater resources, FAO Aquastat, 2022) were used to assess relationships with desalination research and production. Research productivity was measured as the total number of publications and production was represented by desalination capacity ($m^3 d^{-1}$) for each country/nation in the study. The datasets provided information on GDP, population, and water stress up to the year 2020.

To explore these relationships, correlation analyses were conducted using Pearson's correlation coefficient (r), which measures the strength and direction of linear associations between two continuous variables. The coefficient ranges from −1 (perfect negative correlation) to +1 (perfect positive correlation), with values close to 0 indicating weak or no correlation. Linear regression analyses were then performed to further characterize the nature of significant associations. For all tests, p-values were reported, representing the probability that the observed relationship occurred by chance. A threshold of $p < 0.05$ was used to denote statistical significance. p-values were adjusted for multiple testing using the Bonferroni correction to reduce the likelihood of type I error.

All statistical analyses were performed in R (RStudio v4.3.3, 2024) using the rstatix package for the correlation matrices.

3 Results

3.1 Historical trends

The *SCOPUS* search yielded a total of 2,718 citations, of which 1,899 (70%) met the inclusion criteria for this study. The first publication studying desalination in the Middle East was in 1972 (Shelef et al., 1972), yet, before 1998, fewer 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 (Figure 2). 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.

3.2 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 3. 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 (Figure 3, 'All Years').

3.3 Authorship trends

Authorship trends revealed that most desalination research was conducted by authors affiliated with Middle Eastern institutions at

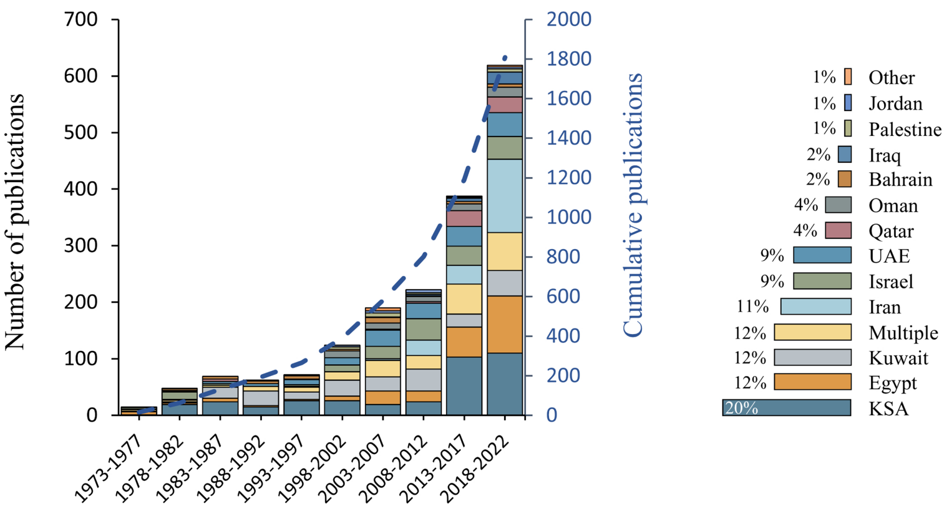

FIGURE 2
Historical trends in desalination research across the Middle East by 'Studied Country'. Bars represent the number of publications over four-year intervals from 1973 to 2022, grouped by the 'Studied Country'. The dashed line shows the cumulative number of articles over 50 years, while the legend (right) shows the cumulative percentage of publications by targeted country.

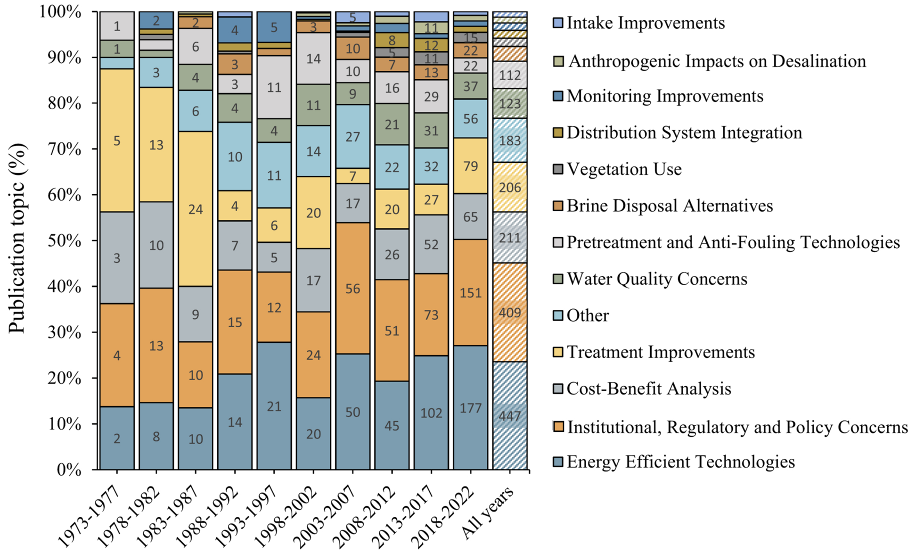

FIGURE 3
Historical trends in publication topics. Historical trends (%) in publication grouped by 'Publication Topic' over five-year intervals. The last column on the right shows the total number of publications.

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 (Figure 4A). 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. Figure 4B 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 (Figure 4B and Supplementary 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%) (Supplementary Table S5).

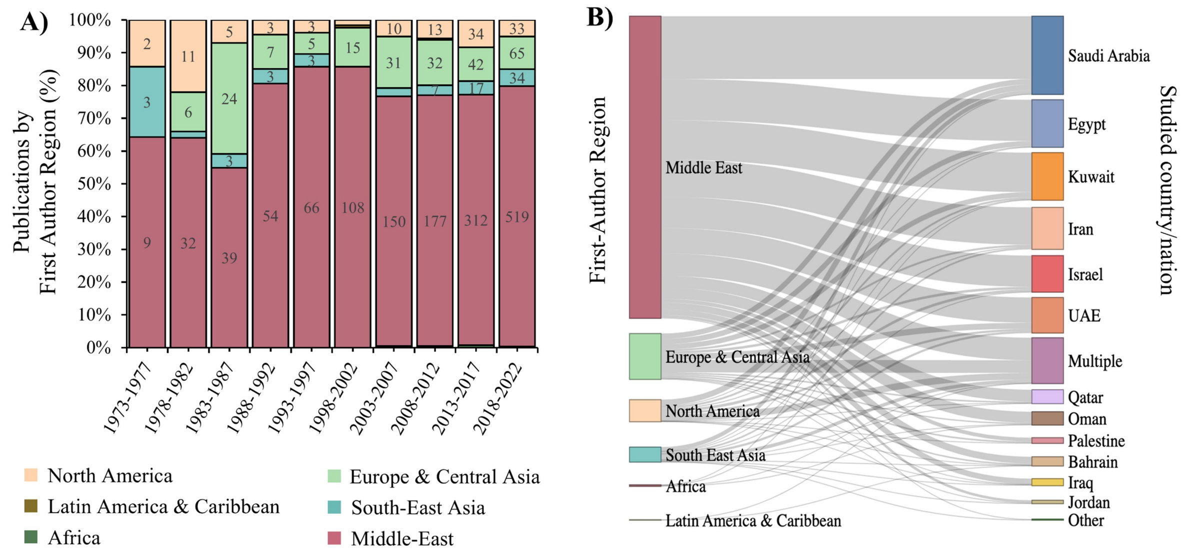

FIGURE 4
Authorship trends in desalination research in the Middle East. **(A)** Temporal trends in the proportion of publication of studies targeting the Middle East grouped by 'First-Author Region' (i.e., the region where the research institution hosting the lead researcher was located). **(B)** Left to right: flow of 'First-Author Region' to 'Studied Country' (i.e., the country target of the research).

3.4 Scientific productivity and water desalination capacity

Desalination water production capacity and publication quantity differed significantly among the Middle Eastern countries/nations included in this study (Figure 5 and Supplementary 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 (Supplementary Table S6).

3.5 Statistical analyses

Despite socio-economic differences among Middle Eastern countries in key areas such as GDP, population and water stress (Supplementary 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, $r_{[15]} = 0.83$, $p < 0.001$) (Figure 6A). 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, $R^2 = 0.69$). However, as these are correlations, they cannot establish causation. It remains unclear whether higher GDP drives greater investment in desalination research and infrastructure or whether expanding desalination capacity and research output contribute to stronger economic performance (Figure 6B, top left and right panels). A significant and strong positive correlation was also found between publication volume and desalination capacity ($r_{[15]} = 0.74$, $p = 0.01$), with a moderate positive linear relationship ($y = 43.4 + 16.2$ x, $R^2 = 0.54$) (Figures 6A,B bottom panel). This suggests that countries investing in desalination research are also more likely to operate substantial desalination infrastructure and vice versa. In contrast, moderate positive correlations between the number of publications and population size ($r_{[15]} = 0.43$) or water stress ($r_{[15]} = 0.45$) 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 association with population size ($r_{[15]} = 0.03$) (Figure 6A).

3.6 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, TVC) towards research on membranes (i.e., RO, FO, U/M/NF) and renewable technologies (i.e., Solar Stills, HDH) (Figure 7A). Specifically, 'Thermal – Evaporation' desalination research comprised 41% of the discourse on desalination technologies up until the late 1990s but has since declined to less

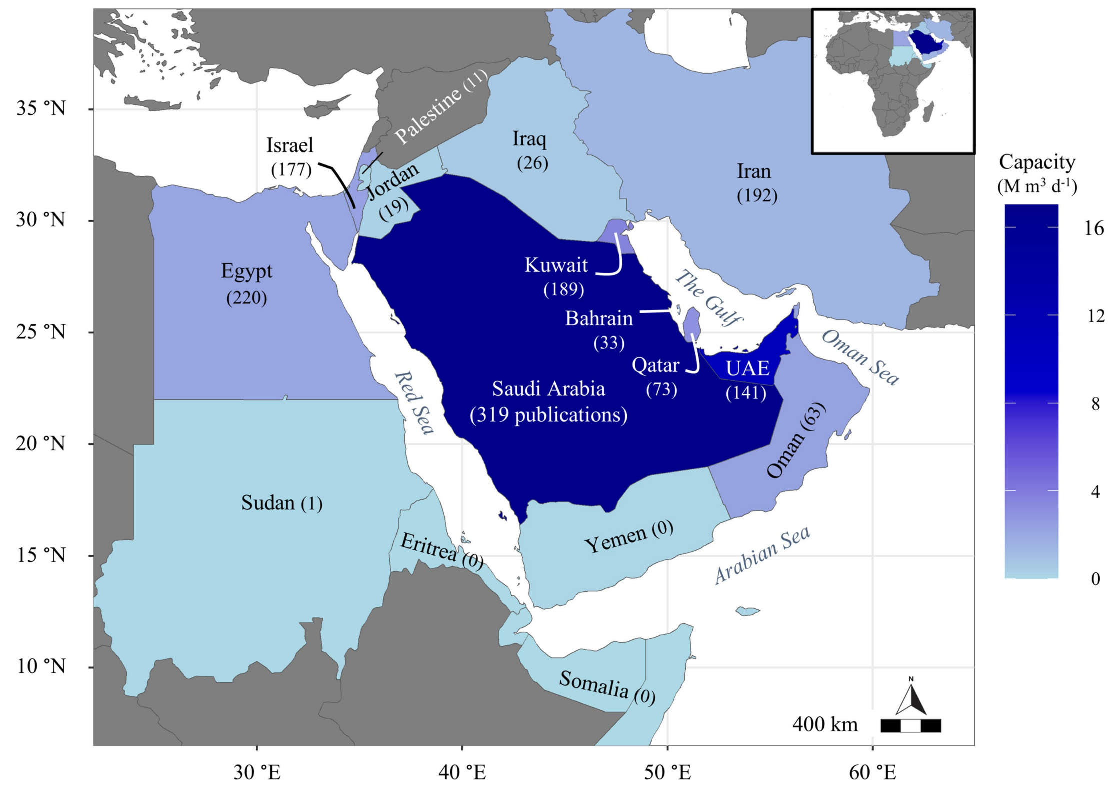

FIGURE 5
Research productivity and water desalination capacity in the Middle East. Color scale corresponds to desalinated water production capacity (million m^3 d^{-1}) in 2022. Bracketed numbers adjacent to country names represent the cumulative number of publications (as of December 2022) on water 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). (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 'rnaturalearthdata').

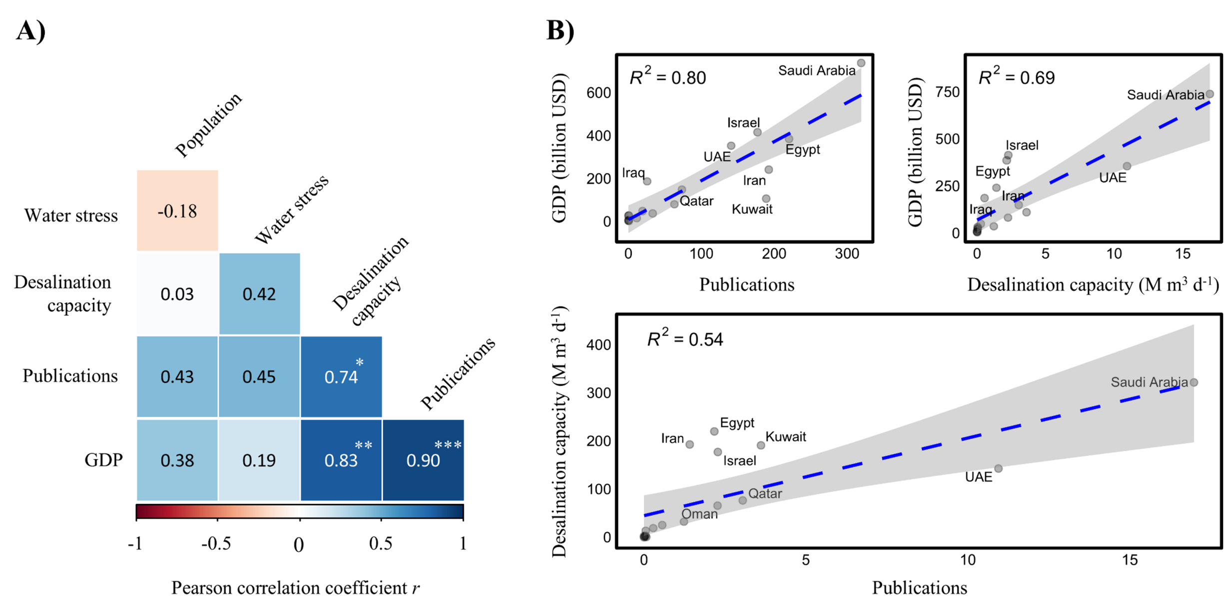

FIGURE 6
Correlation analysis and scatterplots of population, desalination capacity, number of publications, GDP and water stress. **(A)** Correlation matrix assessing associations between population, desalination capacity, number of publications, GDP and water stress. Numbers indicate the *r* value. 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.

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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 shares 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 (Figure 7B). 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 (Kolmogorov–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 (Figure 7B). 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' (Figure 7C).

4 Discussion

Over the past half-century, and particularly in the past two decades, research on desalination and water production has advanced at an unprecedented rate globally. In the Middle East, socio-environmental characteristics have positioned the region as a critical location for the 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, intensifying droughts and threatening freshwater supply, the importance of desalination in the Middle East is expected to grow even further.

Our findings revealed 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

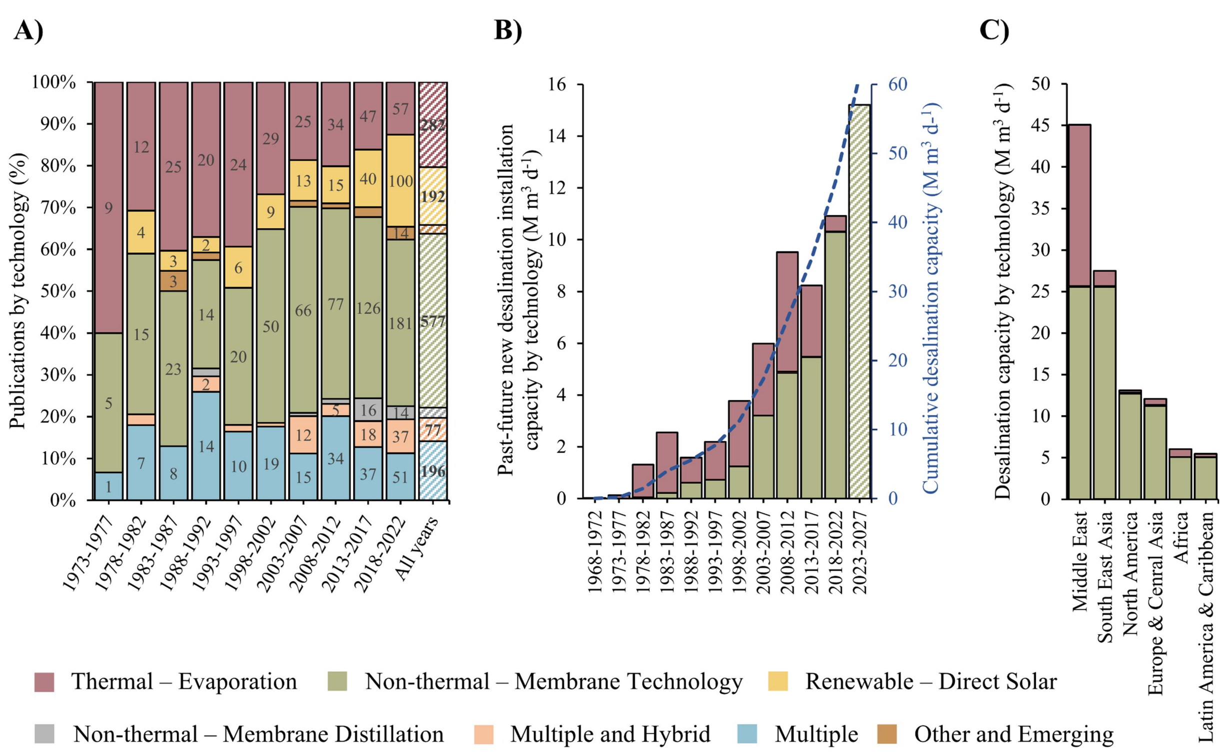

FIGURE 7
Comparisons between scientific research (publications) and water production (desalination capacity) by technology. **(A)** Changes in percentage of publications by desalination technology over time; **(B)** trends in past and future newly installed desalination capacity by technology over time; **(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).

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 13 research themes: 'Energy Efficiency Technologies', 'Institutional, Regulatory and 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 Technologies', 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_2O 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 (Global Clean Water Desalination Alliance "H20 minus CO2", 2015; Masdar, 2018).

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 (e.g., El-Saie et al., 2001; Golkar et al., 2017), covering topics ranging from the integration of renewable energy with various desalination technologies (e.g., Ben-Mansour et al., 2019; Shannak and Alnory, 2020), to the comparative evaluation of concentrated solar power costs (e.g., Soomro and Kim, 2018; Jalili Jamshidian et al., 2022). 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 and 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 (e.g., Al-Senafy et al., 2003; Atiq Ur Rehman et al., 2022), site selection considerations (e.g., Gholamalifard et al., 2022), environmental impacts (e.g., Lattemann and Höpner, 2008; Al-Dousari et al., 2012; Mannan et al., 2019), public-private partnerships (e.g., Mimi and Marei, 2002), water pricing (e.g., Wachtel, 2007), institutional frameworks (e.g., Fadlelmawla, 2009; Al Jabri et al., 2019), multi-criteria decision analysis (e.g., Aliewi et al., 2017; Dweiri et al., 2018), transboundary water issues (e.g., Walschot, 2018; Rusteberg et al., 2022), the water-energy-food nexus (e.g., Siddiqi and Anadon, 2011; Alhanaee and Meshkati, 2020), carbon footprint and life cycle assessments (e.g., Al-Shayji and Aleisa, 2018; Aleisa et al., 2022). 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 10 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 and Baddour, 2014; Omerspahic et al., 2022). This is especially critical in the Red Sea and the Arabian/Persian Gulf, both semi-enclosed, hypersaline basins (mean salinity: 38 and 42 PSU, respectively), where ongoing desalination activity may further increase salinity levels, with potential consequences for both marine biodiversity and efficiency of desalination operations (Paparella et al., 2022).

Turning to the technologies associated with these thematic areas, it becomes evident that the region has experienced a gradual 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, early research predominantly focused on traditional 'Thermal – Evaporation' methods, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). A notable shift began in the late 1990s, when research attention increasingly moved away from these fuel-intensive technologies towards more energy-efficient and environmentally sustainable 'Non-thermal – Membrane Technologies', such as Reverse Osmosis (RO), Forward Osmosis (FO) and Membrane Distillation (MD). Our data suggest that by the early 2000s, research on membrane desalination had surpassed thermal technologies in volume, a trend that was soon reflected in industrial desalination practices.

Historically, thermal desalination technologies were widely adopted 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 their greater tolerance to high salinity and challenging feedwater conditions (Figure 7C) (Ahmed et al., 2021; Moossa et al., 2022). However, significant advances in membrane materials, module design, pretreatment processes and energy recovery systems during the 1980s and 1990s contributed to a sharp reduction in energy consumption and CO_2 emissions associated with membrane-based desalination (Ahmed et al., 2021; Lee et al., 2011). These improvements have rendered membrane technologies not only more energy efficient but also more economically and politically viable for large-scale deployment across the region (Moossa et al., 2022; Feria-Díaz et al., 2021). Consequently, while thermal desalination plants dominated installations throughout the twentieth century, the adoption of membrane-based technologies, particularly RO, accelerated in the early 2000s and has since become the prevailing choice for new installations. Today, all planned and ongoing desalination projects in the Middle East are expected to utilize RO, underscoring the region's full transition toward non-thermal desalination technologies.

Ongoing efforts to improve desalination sustainability are exploring the integration of renewable energy options with different desalination technologies. Studies indicate that thermal desalination is better suited to solar thermal power, while RO and Electrodialysis (ED) are more compatible with photovoltaic and concentrated solar power systems (Ghermandi and 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 and 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. 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 to further increase salt rejection and reduce fouling (Feria-Díaz et al., 2021; Wang et al., 2018). On the other hand, RO hybridization with thermal technologies 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 and Bosurgi, 2022). For example, in some areas of research, over 50% of the 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 and Burt, 2016; Friis and Burt, 2020). However, our findings 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 (Supplementary Tables S4, S5), while 'international' authors appeared more inclined to focus on pan-regional or global topics (Supplementary 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 and Al-Thani (2022) presented perspectives on endophytes and halophytes for the remediation of industrial wastewater and saline soils, tailored to local 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 and 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 and 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 and 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.

4.4 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 higher GDPs. In contrast, water stress levels and population size were not significantly related to either desalination research or freshwater production. These findings indicate that wealthier nations may be better positioned to make the substantial investments required for the research, development, installation and maintenance of desalination infrastructure. Moreover, the relationship may be bidirectional: the availability of desalinated water likely contributes to greater water security, which in turn supports economic growth and stability.

Over the past 15 years, desalination has increasingly become a national research priority across much of the Middle East, particularly in wealthier Gulf nations. This prioritization is evidenced by the establishment of major academic institutions and research centers dedicated to desalination, water reuse and sustainability. Notable examples include the Water Desalination and Reuse Center at King Abdullah University of Science and Technology (KAUST, founded in 2009 and currently the fourth most prolific institution in desalination research in the region), the Qatar Environment and Energy Research Institute (QEERI) at Hamad Bin Khalifa University (established in 2010 and ranking fifth), the Water Research Centre at Sultan Qaboos University (SQU, launched in 2010 and ranked sixth), the Renewable Energy Water Desalination Program at the Masdar Institute in the UAE (initiated in 2013 and ranked fifteenth) and the Water Research Center (WRC) at New York University Abu Dhabi (center launched in 2020 and ranked thirtieth) (Supplementary Table S7). This trend is consistent with previous bibliometric reviews, which noted a rapid rise in desalination publications from Gulf institutions since the mid-2000s (Zyoud and Fuchs-Hanusch, 2015; Zapata-Sierra et al., 2021; Chowdhury et al., 2024), though those studies did not explicitly link this surge to parallel increases in production capacity or government funding.

This rapid institutional expansion and funding emphasis helps explain why Gulf states, despite their small population and very limited natural freshwater resources, now exhibit some of the highest per capita rates of desalinated water production worldwide. For instance, Saudi Arabia remains the most prolific producer of both desalination research and desalinated freshwater, with similar patterns observed in smaller Gulf States such as the UAE, Qatar, Kuwait and Bahrain. Heavy government subsidies in these countries have ensured widespread availability of desalinated water, contributing to some of the highest per capita water consumption rates globally (Sherif et al., 2023). While this strategy has secured water availability in the short term, is also reinforces dependence on desalination, further increasing demand. Implementing more effective water policies and management practices could not only improve water supply but also help curb water demand, which will be particularly important considering predicted population growth.

4.5 Global comparisons and future directions on Middle East desalination research

Despite a population of just 400.3 million, representing ~5% 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 photovoltaics) 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).

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.

5 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.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DD'A: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MA-M: Conceptualization, Data curation, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. JB: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. Artificial intelligence tools (ChatGPT, OpenAI) were used during the manuscript preparation phase to improve grammar, clarity, and fluency of the English language. All conceptual content, analysis, and interpretations were developed entirely by the authors.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1672360/full#supplementary-material

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