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An investigation of desalination research in Saudi universities

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ABSTRACT

A number of cost-saving novelties in seawater desalination technology over the years have transmuted this once costly option of last resort into a viable water supply alternative. The scarcity of freshwater resources and the increasing gaps between demand and supply in the arid regions continue to drive the need for desalinated water. Saudi remains one of the leaders in desalination technology and the largest producer of desalinated water. Hence, it is necessary to document the contributions of Saudi universities and various funding agencies in the development of these technologies. This study investigated research activities in the field of desalination among Saudi universities. Using the ISI Web of Science database, the word DESALINATION as a search word returned a total of 13,457 publications. The breakdown of publications based on the top 10 countries gives: USA (917), China (643), Spain (412), South Korea (307), Australia (291), Saudi Arabia (255), Israel (256), India (208), Germany (257) and England (216). The study will process all the 255 articles returned for Saudi and analyze these articles according to funding agencies, universities, type of contribution (theoretical or experimental contribution), number of authors in each publication, journal types, paper citation and year of publication.

Keywords: Desalination; Freshwater; Saudi Arabia; Groundwater aquifers; Universities; Research; Scientometrics

1. Introduction

Water resources are abundant in the earth's crust, but freshwater resources are not evenly distributed across the globe. The uneven distribution of freshwater (renewable water sources) leads to the classification of world regions as either water scarce or water surplus. These freshwater sources are usually in the form of surface water or underground waters (groundwater aquifers). Table 1 gives an overview of countries with water scarcity and water surplus [1,2]. According to Falkenmark Water Stress Indicator, a country with renewable water of more than 1,700 m^3/capita-year is not water scarce, while countries with less than 1,000 m^3/capita-year are classified as water scarce. This benchmark for water scarcity is generally accepted and widely used. Apart from the uneven distribution (natural availability) of freshwater sources, a number of other factors contribute to a region's water scarcity. Such factors include population growth rate, industrialization, economy and local climate. Population growth is inevitable in most parts of the developing world; increase in earnings as a result of economic growth improves health systems, technologies and civilization, and has an influence on the size of a family. The Middle East countries' population growth rate is expected to rise due to high income from sales of crude oil. Increasing population growth in the Middle East will put further stress on an already water scarce region. Fig. 1 shows the trend in population, total annual freshwater withdrawals (total annual water withdrawals refer to total water withdrawals with water from desalination plants).

Desalination is now considered a tested means of providing freshwater on a large scale throughout the world [3–5]. Over the years, continual improvements have taken place, and the available technologies are now more efficient and dependable at much reduced cost [3]. Thermal technologies have dominated the scene for many years with the use of multi-stage flash (MSF) as the "horse engine" for freshwater production from the sea. This technology is still

Table 1
Distribution of renewable freshwater resources on a per capita basis [1,2]

Country	Renewable water (m^3/y)				
	Total (km^3/y)	Per capita (2000)	Per capita (2025 low)	Per capita (2025 med)	Per capita (2025 high)
Kuwait	0	0	0	0	0
UAE	0	77	61	58	55
Saudi Arabia	2	118	63	59	56
Jordan	1	142	87	81	76
Libya	1	151	107	100	95
Yemen	4	223	89	85	82
Oman	1	394	196	185	177
Tunisia	4	412	348	316	291
Israel	3	464	354	330	310
Algeria	14	472	361	335	313
Morocco	30	1004	779	714	665
Egypt	69	1009	789	723	666
Burkina Faso	20	1690	808	773	745
Ethiopia	110	1749	1020	970	932
Somalia	16	1789	778	741	714
Denmark	6	1116	1133	1107	1083
Zimbabwe	14	1117	820	755	700
South Africa	50	1154	1251	1142	1052
Lebanon	5	1373	1117	1048	992
Korea, Rep.	70	1493	1378	1341	1307
Belgium	16	1561	1602	1568	1535
Poland	63	1632	1728	1691	1656
Malawi	19	1645	1022	952	907
Pakistan	255	1805	1063	1016	973
Iran	129	1827	1400	1293	1206
India	1908	1891	1511	1411	1323
Germany	178	2170	2299	2256	2215
China – all included	2830	2206	2028	1912	1823
Bulgaria	18	2290	3027	2971	2917
Eritrea	9	2405	1302	1246	1196
Nigeria	280	2459	1454	1380	1312
United Kingdom	147	2474	2456	2400	2346
Dominican Republic	21	2508	2057	1922	1805
Tanzania	89	2534	1592	1474	1377
Sri Lanka	50	2642	2370	2219	2084
Moldova	12	2724	3010	2887	2776
Ghana	53	2756	1852	1720	1609
Syria	45	2761	1754	1631	1524
Armenia	11	2799	2916	2837	2791
Spain	112	2809	3049	2998	2950
Ukraine	140	2816	3603	3528	3458
France	170	2870	2783	2709	2642
Niger	33	3000	1326	1263	1216
United States	2478	8749	7439	7145	6775

Note: The data (from World Bank, United Nations, and Organization for Economic Cooperation and Development (OECD)) were compiled by Population Action International, and the original table was edited by the author to reduce the list of countries.

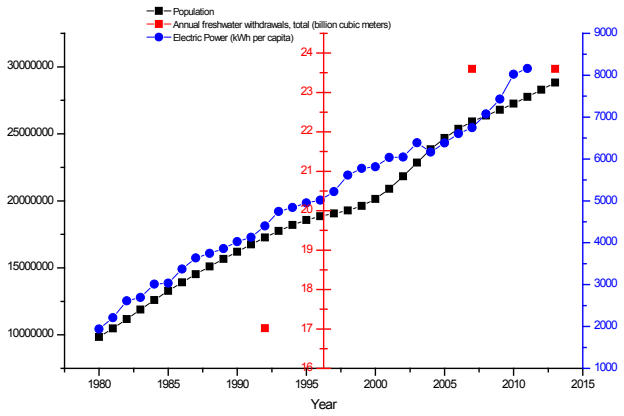

Fig. 1. Population, annual freshwater withdrawal and electric power trends in Saudi Arabia [1].

evolving as multi-effect evaporation (MEE) is now replacing the MSF as the latest state-of-the-art thermal technology. However, MSF thermal technology is still common and in operation in Middle East countries due to the availability of crude oil resources in the region. Although MEE technology is extending its lead in the region's newly constructed desalination plants, one potential viable alternative option for desalination is membrane desalination technology [6,7]. The growth of membrane desalination technology, especially reverse osmosis (RO), is now attracting attention among players in the industry due to its lower energy requirement as compared to thermal technology. In fact, RO is now the leading technology in desalination. The theoretical minimum energy expenditure for RO is between 3 and 7 kJ/kg, while, in practice, due to losses, energy expenditure of 11–60 kJ/kg has been recorded, which is still low as compared with the expenditure energy requirement of thermal technology. It is expected that the theoretical minimum energy expenditure will continue to improve as the technology matures. The Kingdom of Saudi Arabia is situated in the Arabian Peninsula, a desert environment with lack of freshwater sources. The Arabian Peninsula is bordered by the Red Sea on the west and the Indian Ocean to the southeast, providing a huge source of feed water for the desalination processes. Saudi, with more than 30 desalination plants (government and private owned), produces about 1.3 billion m^3 of desalinated seawater per year at an average cost of 0.80 US $/$m^3$ [7–9]. "Desalination" is a household word in Saudi, and the government continues to invest in desalination technologies to meet the growing population of its citizenry. This work archives the research contributions of tertiary institutions in Saudi in the development of desalination technologies. The application of Scientometrics in analyzing scientific publication (mainly from the ISI database) will help to advance knowledge within a given subject or about any nation [10,11]. Scientometrics has been used for quantitative analysis and for obtaining statistics that measure the contribution of scientific publications to the advancement of knowledge [12–14]. According to Celiktas et al. [12], scientific publications represent current research trends that can be used to identify the focus of present, past or future research.

The focus of this work was to trace research trends and scientific contributions in the field of desalination in the Kingdom of Saudi Arabia using the keyword "Desalination" in the ISI database between 1997 (when the first paper on desalination from a Saudi tertiary institution appeared in a journal on the ISI Web of Science) and July 2013.

2. Desalination technology in the Kingdom of Saudi Arabia

Freshwater is basic to human continued existence, as well as being an indispensable element of its formation and growth. Saudi's location, a very hot, dry, desert region, lacks adequate quantity of natural inland freshwater resources, which has prompted the use of seawater desalination to meet domestic freshwater demands. This geographic location, like other GCC countries, has turned seawater into a stable and economically feasible source of freshwater. This freshwater supplied from the sea, using mainly thermal desalination technology known as MSF evaporation, is powered by fossil fuel. The abundance of fossil fuel in the region is a major drive for the continued use of thermal desalination technology. Saudi has embraced MSF technology due to its dual purpose of providing water and electrical power. These dual-purpose systems have played a critical role in sustaining the country's rapid economic and social development. About 60% of daily water demand is desalinated. Of this, 40% comes from Saline Water Conversion Corporation (SWCC), the government-owned company's desalination stations, and 20% from stations operated by the private sector. The SWCC operated/proposed plants and transmission overview are shown in Fig. 2. Table 2 shows the plants details (single- or dual-purpose plants), type of desalination process and year commissioned. The first desalination plant, Jeddah II MSF plants, was commissioned in 1978 with a design capacity of 37,916 m^3/d and 71 mW of electricity. The MSF technology was largely used for freshwater production until 1983 when the first RO system was introduced in Saudi Arabia. The first RO system was a small-size membrane system with a design capacity of 1,952 m^3/d. This system was later

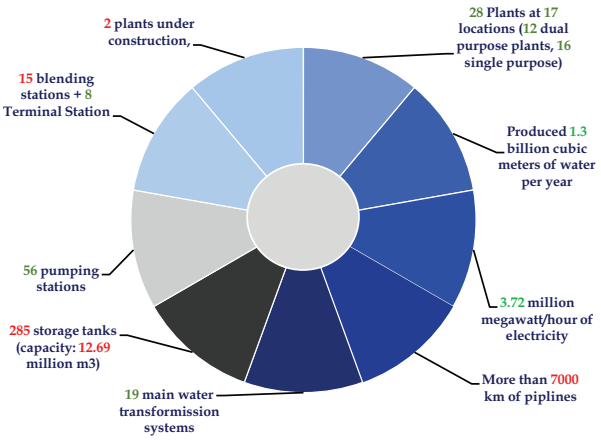

Fig. 2. Saline Water Conversion Corporation (SWCC) operated/proposed plants and transmission overview [15].

Table 2
Governemnt operated Desalination plants in Saudi

Location/phase name	Year of operation	Process	Designed exported capacity (m^3/d)	Electric power export (mW)
Plants currently in operation				
Jeddah 2	1978 (decommissioned)	MSF	37,916	71
Jeddah 3	1979 (decommissioned)	MSF	75,987	200
Jeddah 4	1981	MSF	190,555	500
Yanbu 1	1981	MSF	94,625	250
Al-Khobar 2	1982	MSF	191,780	500
Al-Jubail 1	1982	MSF	118,447	238
Al-Jubail 2	1983	MSF	815,185	762
Al-Birk 1	1983	RO	1,952	-
Al-khafji 2	1986	MSF	19,682	-
Ummluj RO	1986	RO	3,784	-
Al-Aziziyah 1	1987	RO	3,870	-
Jeddah RO 1	1989	RO	48,848	-
Al-Shoaibah 1	1989	MSF	191,780	157
Duba 3	1989	RO	3,784	-
Al-Shuqaiq 1	1989	MSF	83,432	62
Haql 2	1990	RO	3,784	-
Jeddah RO 2	1994	RO	48,848	-
Yanbu 2	1999	MSF	120,096	35
Yanbu RO	1999	RO	106,904	-
Al-Jubail RO	2002	RO	78,182	-
Al- khobar 3	2002	MSF	240,800	311
Al-Shoaibah 2	2002	MSF	390,909	340
Al-Qunfidah 1	2008	MED	7,740	-
Al-Wajh 3	2009	MED	7,740	-
Ummluj 3	2009	MED	7,740	-
Rabigh 2	2009	MED	15,480	-
Farasan 2	2009	MED	7,740	-
Jubail 2	2009	MSF	800,000	2,750
Jeddah RO 3	2013	RO	240,000	-
Ras Al-Khair	2014	MSF/RO	1,025,000	2,600
Plants under construction				
Yanbu 3	2015	MSF	550,000	2,500
Plants under study				
Duba 4	-	RO	9,000	-
Alwajh 4	-	RO	9,000	-
Haqal 3	-	RO	9,000	-
Rabigh	-	MSF	1,000,000	-
Jubail 3	-	MSF	1,500,000	-
Jeddah RO 4	-	RO	400,000	-
Al Khubar 4	-	MSF	925,000	-
Al Khafji 4	-	MSF	45,000	-
Shuqaiq 3 First stage	-	MSF	225,000	-

followed by two other small-size RO systems of 3,784 and 3,870 m^3/d in 1986 and 1987, respectively.

These RO systems were small compared with the existing MSF plants. The first medium-size RO system was commissioned in 1989 with 48,848 design capacity. Large-scale RO systems did not come into play until 1999 when a 106,904-design-capacity RO was commissioned in Yanbu. The largest RO system in Saudi was not commissioned until 2013, when a 240,000-m^3/d plant was built in Jeddah. Also, commissioned were five small-scale multiple-effect distillation (MED) desalination plants between 2008 and 2009, of which four were 7,740 m^3/d capacity and the fifth of 15,480 m^3/d.

3. Methodology

This work has followed the methodology of Celiktas et al. [12], the source of the data was the ISI Web of Science that covers over 23,000 academic and scientific journals, 192,000 conference proceedings, 23,000,000 patents, 9,000 websites and 5,000 books in 256 scientific disciplines from 90 countries, with 25 million cited references added annually, with coverage from 1950.

Data used in the study were acquired from the ISI Web of Science portal based on the author's affiliation addresses recorded as "Saudi or Kingdom of Saudi Arabia" by using the keyword "Desalination" in title and topic from 1997 to 13th July 2013. The keyword "Desalination" returned a total of 13,457 publications between 1997 and 2013 with the breakdown of the top nine countries as shown in Fig. 3.

The 255 articles for Saudi were processed according to distribution of publications over the years: the authors, the authors' institutions, the journals, the number of citations, the keywords, international collaborations and funding agencies. All publications were classified into their subfields and later classified as either experimental study or theoretical study (Table 3).

4. Publications processing and discussion of results

This work processed a total of 255 publications with desalination as the keyword in the title and/or topics in order to analyze the research contribution of institutions in Saudi Arabia based on the database of the ISI Web of Science between 1997 and 2013, published in 64 different journals. Fig. 4 shows the yearly progression of publications, and it will be observed that the number of publications grew sharply from 2009. About 56.87% of total publications occurs between 2010 and 2013 with the number of articles published in 2013 (January–July) accounting for 19.61% of the total (Table 4). According to the subcategorization as seen in Table 4, 30.55% of the articles are on membrane processes, 14.21% on solar desalination, 12.55% on distillation processes and 3.14% on Policy and Economics. In addition, from Table 4, it is seen that the desalination research area changes from distillation to membrane processes as the year progresses to 2013. This shows similar trends to the global research focus from

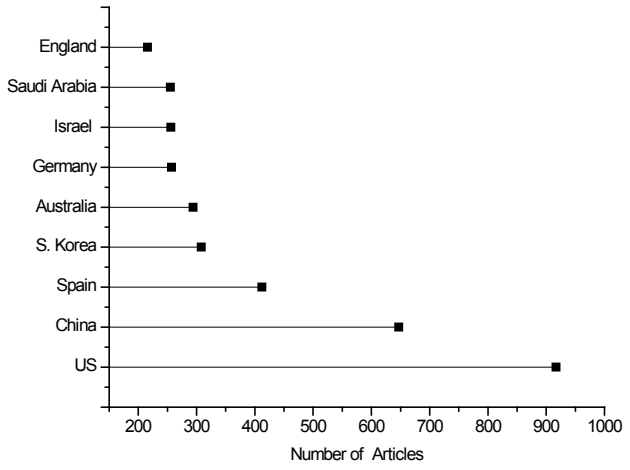

Fig. 3. Number of articles from 1997 to 2013.

Table 3
Classification of desalination publications according to the scientific categories (1997–2013)

Classification of publications in various desalination subgroups	Number of publications	Experimental study	Theoretical/ numerical/ simulation study
Distillation	32	15 (46.88%)	17 (53.12%)
Multi-stage flash distillation (MSF)	28	13	15
Multiple-effect distillation (MED/ME)	2	-	2
Vapor compression (VC)	2	2	-
Ion exchange	1	1 (100%)	-
Membrane processes	79	46 (58.22%)	33 (41.78%)
Electrodialysis reversal (EDR)	-	-	-
Reverse osmosis (RO)	45	21	24
Nanofiltration (NF)	21	14	7
Membrane distillation (MD)	4	2	2
Forward osmosis (FO)	9	9	-
Freezing desalination	-	-	-
Geothermal desalination	3	-	3 (100%)
Wind desalination	1	-	1 (100%)
Solar desalination	37	16 (43.24%)	21 (57.76%)
Solar humidification–dehumidification (HDH)	22	7	15
Solar still	15	9	6
Adsorption desalination	6	3 (50%)	3 (50%)
Nuclear desalination	4	-	4 (100%)
PV/CSP desalination	4	-	4 (100%)
Hybrid desalination system	7	1 (14.3%)	6 (85.7%)
Policy/Economics	8	-	8 (100%)
Other desalination publication	73	40	33
Total (%)	255 (100)	122 (47.8)	133 (52.2)

distillation processes (MSF and MED) to membrane processes (RO, forward osmosis, and membrane distillation).

The distribution of the number of publications that appeared in journals and were indexed in the ISI is given in Fig. 5. More than half of all publications (53.34%) appeared in two journals and the rest in 64 journals. The majority of the articles were published in *Desalination (37.26%), Desalination and Water Treatment (16.08%), Renewable and Sustainable Energy Reviews (5.1%), Journal of Membrane Science (3.92%), Energy (3.53%), Renewable Energy (2.36%), Water Research (1.57%), Applied Thermal Energy (1.57%)* and *International Journal of Heat and Mass Transfer (1.57%)*. Fig. 6 shows the yearly citation of the articles from 1998 to 2013 (July) with the peak citation in 2012. Fig. 7 shows the author(s) with highest number of publications between 1997 and 2013.

Fig. 8 shows the distribution of publications by the top 13 Saudi institutions (universities and government agencies responsible for water treatments) with King Saud University (KSU) and King Fahd University of Petroleum and Minerals (KFUPM) having the highest share with 17.6% each. The SWCC, a government agency responsible for desalinating seawater in Saudi, published 16.1% of the total published articles. The language of communication in all the processed articles was English, and 16.47% of them had single authorship (Fig. 9). Classification of the publications according to two descriptors showed that 47.8% were experimental studies and 52.2% were theoretical/numerical/simulation (Table 3).

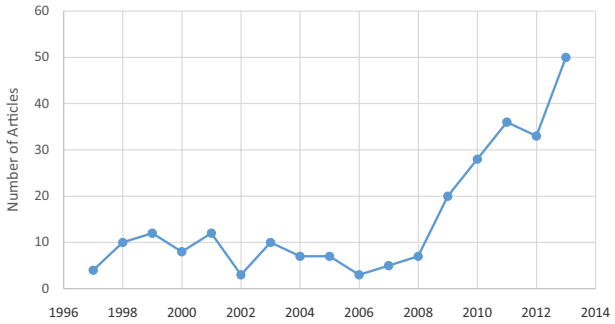

Fig. 4. Trends of publication output from 1997 to 2013.

4.1. Distillation processes

A total of 32 publications on distillation (Table 5) was published, accounting for 12.55% of the total publications, with the contributions of 98 authors between 1997 and 2013,

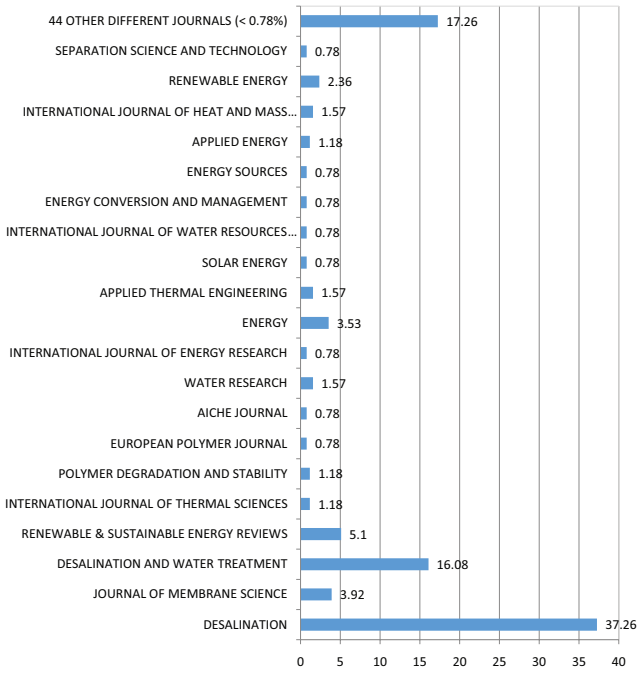

Fig. 5. Distribution of publication in journals expressed as percentage between 1997 and 2013.
Note: Desalination and Water Treatment is from 2009 to 2013.

Table 4
Publication output from 1997 to 2013

Classification of sub-fields	1997–2000 (%)	2001–2003 (%)	2004–2006 (%)	2007–2009 (%)	2010 (%)	2011 (%)	2012 (%)	2013 (%)	Total (%)
Distillation	4.71	2.35	0.39	1.18	2.35	0.78	0.00	0.78	12.55
Ion exchange	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Membrane processes	3.49	2.35	1.57	3.92	1.18	4.31	5.88	7.84	30.55
Freezing desalination	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Geothermal desalination	0.00	0.00	0.00	0.00	0.78	0.00	0.00	0.39	1.18
Wind desalination	0.00	0.00	0.00	0.39	0.00	0.00	0.00	0.00	1.00
Solar desalination	0.78	0.00	1.18	2.35	2.75	1.96	1.96	3.14	14.12
Adsorption desalination	0.00	0.00	0.00	0.39	0.00	0.00	0.00	1.96	2.35
Nuclear desalination	0.00	0.78	0.39	0.00	0.00	0.39	0.00	0.00	1.57
PV/CSP desalination	0.78	0.00	0.00	0.00	0.00	0.78	0.00	0.00	1.57
Hybrid desalination system	0.39	0.00	0.78	0.00	0.00	0.00	0.00	1.57	2.75
Policy/Economics	0.39	1.18	0.00	0.00	0.39	0.39	0.00	0.78	3.14
Other desalination publication	2.35	2.75	2.35	4.31	3.14	5.49	4.71	3.14	28.24
Total (%)	12.90	9.80	6.67	12.55	10.59	14.12	12.55	19.61	100.00

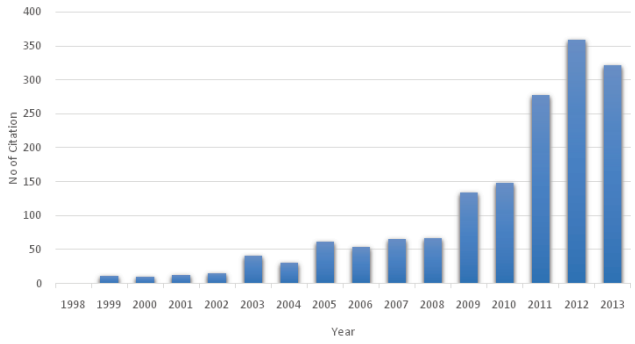

Fig. 6. Yearly article citation.

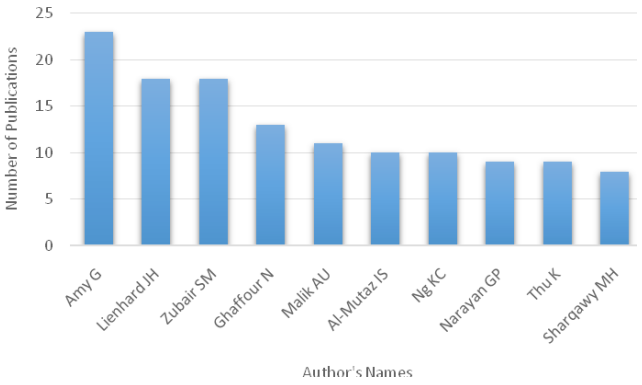

Fig. 7. The top published authors between 1997 and 2013.

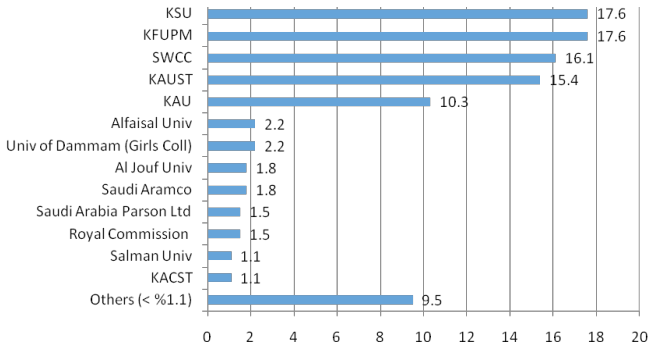

Fig. 8. Distribution of publication among Saudi institutions expressed as percentage between 1997 and 2013.

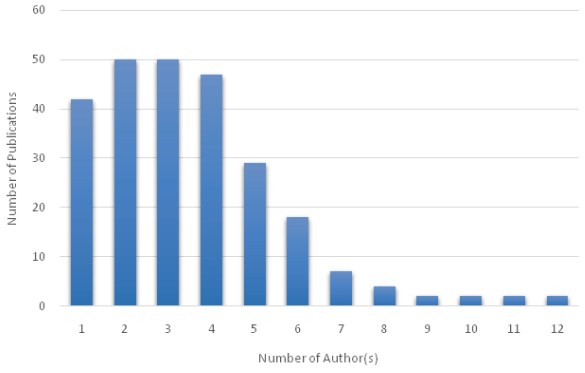

Fig. 9. Number of authors in publication.

making it the third highest research area of interest by Saudi researchers. Saudi depends on the distillation processes for its daily freshwater needs, and distillation processes account for about 85% of freshwater production (Table 2). There are 28 desalination plants operated by the Saudi government with a daily production of 4,866,735 m^3/d (assuming the combined MSF/RO of 1,025,000 is fully operational), of which MSF account for 84.79% (3,257,291 m^3/d), MED 1.21% (46,440 m^3/d) and RO 14.00% (538,004). It will be observed from Table 4 that early research interest was on the MSF distillation process because that was the main means of freshwater production. Research on distillation processes declined until 2010 due to the construction and installation of new MED distillation processes in 2008 and 2009 (Table 2). Among the 32 publications on distillation, 46.88% were experimental studies while 53.12% were theoretical/numerical/simulation (Table 3). Single authorship accounts for just 8.2%, double authorship for 6.1%, while more than two authors accounts for 85.7%. In total, distillation publications appeared in seven different journals with the top three being *Desalination*, *Desalination and Water Treatment*, and *Journal of Material Performance* (Table 5).

A total of 37 different institutions contributed to the distillation research publication in Saudi with five international institution collaborations. The top three institutions are SWCC, KSU and King Abdulaziz University. More than 10 funding agencies/organizations were identified to have funded research in this field. Massachusetts Institute of Technology (MIT) is also identified as the top international institution that collaborates in distillation research in Saudi. The papers were cited 94 times; 71.9% of the articles were cited between 1 and 10 times, whereas 28.1% of the articles were never cited. Of the articles never cited, 22.2% were published in 2013. The most cited article was *Early failure of cupronickel condenser tubes in thermal desalination plant* by Asrar et al. [16] with 15 citations.

4.2. Membrane processes

In membrane desalination, there are 79 publications with contributions from 314 authors between 1997 and 2013 (July), making it the highest percentage of articles with the search word "desalination". Among the 79 articles, experimental studies account for 58.22%, while theoretical/numerical/simulation studies account for 41.78% (Table 3). Single and double authorships are very rare, accounting for 3.2% and 2.2%, respectively, while more than two authors accounts for 94.6% of all the articles in the section. The articles under this classification appeared in 18 different journals with the top 3 journals being *Desalination*, *Desalination and Water Treatment*, and *Journal of Membrane Science*, respectively. Article publication in this field has been on the rise since 2011 due to membrane problems faced in the RO plants because of the high concentration of the total dissolved salt in the seawater (Table 4). The main research focus was on RO and nanofiltration, which is in agreement with the problem posed by the RO plants within the country. The small size of these RO plants afforded researchers the opportunities to study them for optimization, especially the membrane. On the other hand, there was a significant increase in terms of publications on forward osmosis, a new direction in membrane desalination.

Table 5
Analysis of different parameters related to "other systems" between 1997 and 2013

	Distillation	Membrane processes	Solar desalination	Hybrid desalination system	Policy/ economics	Other desalination publication
Publication number	32	79	37	7	8	73
No. of authors	98	314	101	27	14	238
No. of single author publication (%)	8.2	3.2	7.9	3.7	28.6	4.2
No. of double author publication (%)	6.1	2.2	10.9	0.0	14.3	10.0
No. of different journals	7	18	5	3	4	38
Top three journals						
1	D[a]	D[a]	D[a]	D[a]	D[a]	D[a]
2	DWT[a]	DWT[a]	DWT[a]	DWT[a]	DWT[a]	DWT[a]
3	MP[a]	MS[a]	E[a]	AP[a]	JWRD	RSER[a]
Top three institutions						
1	SWCC	KAUST	KFUPM	KAUST	KSU	KFUPM
2	KSU	KSU	KAU	SWCC	KAUST	KSU
3	KAU	SWCC	KSU	KFUPM & KAU	KFUPM	SWCC
No. of citations of publication	94	619	169	50	18	533
Articles cited between 1 and 10 times (%)	71.9	69.6	78.4	50	37.5	72.6
Articles never cited (%)	28.1	30.4	21.6	50	62.5	27.4
Articles never cited published in 2013 (%)	22.2	66.7	75.0	100	40.0	40.0

[a]D: *Desalination*; DWT: *Desalination and Water Treatment*; MP: *Material Performance*; MS: *Membrane Science*; E*: Energy*; AP: *Applied Energy*; IJWRD: *International Journal of Water Resource and Development*; RSER: *Renewable & Sustainable Energy Reviews*; SWCC: Saline Water Conversion Corporation; KSU: King Saud University; KAU: King Abdulaziz University; KFUPM: King Fahd University of Petroleum & Minerals; KAUST: King Abdullah University of Science and Technology.

A total of 87 different institutions' authors contributed to the membrane papers, and 58 international author collaborators were identified. King Abdullar University of Science & Technology (KAUST), KSU and SWCC were the top three in membrane desalination research institutions. The papers were cited 619 times; 69.6% of the articles were cited between 1 and 10 times, whereas 30.4% of the articles were never cited. Out of the never cited articles, 66.7% were published in 2013. The most cited article was *A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes (Part 1)* by Hassan et al. [17] with 79 citations. Two other articles with high citation are the work of Zhang et al. [18] on cellulose acetate membranes for forward osmosis and Hassan et al. [19] on nanofiltration–seawater RO, which received 63 and 42 citations, respectively.

4.3. Solar desalination

A total of 37 articles was published in the solar desalination category with the contributions of 101 authors between 1997 and 2013, of which 43.24% were experimental studies and 57.76% were theoretical/numerical/simulation studies (Table 3). Saudi potential for solar application is vast in terms of land area (approximately 2,250,000 km^2) and solar radiation (2,200 kWh/m^2). In terms of authorship, 10.9% of the publications were double authored, whereas 7.9% had single authors. All solar desalination articles appeared in 15 different journals with the top 3 journals being *Desalination*, *Desalination and Water Treatment*, and *Energy Journal*. The top 2 institutions with the highest number of publications in this field were King Fadh University of Petroleum and Minerals and the SWCC. The papers were cited 169 times; 78.4% of the articles were cited between 1 and 10 times, whereas 21.6% of the articles were never cited. The most cited article was *The potential of solar-driven humidification-dehumidification desalination for small-scale decentralized water production* by Narayan et al. [20] with 30 citations. The two other articles with high citation were the work of Narayan et al. [21] on the thermodynamic analysis of humidification dehumidification desalination cycles with 27 citations, and the work of Mistry et al. [22] on the effect of entropy generation on the performance of humidification–dehumidification desalination cycles with 24 citations.

4.4. Hybrid desalination systems

A total of seven articles were published under the hybrid desalination category with the contribution of 27 authors between 1997 and 2013, of which 14.3% were experimental studies and 85.71% theoretical/numerical/simulation studies (Table 3). Single author publication accounted for 3.7% with no double authorship. The articles featured in just three different journals (Table 5). The top three institutions with the highest number of publications in this field are King Abdullah University of Science and Technology and SWCC with King Fadh University of Petroleum and Mineral sharing third place with King Abdulaziz University. The papers were cited 50 times; 50% of the articles were cited between 1 and 10 times; and 50% of the articles were never cited.

4.5. Policy/economics

There are eight articles published under the Policy/Economics category with the contribution of 14 authors between 1997 and 2013, of which all are theoretical studies (Table 3). In terms of authorship, 28.6% of the publications were single authored, whereas 14.3% had double authors. All solar desalination articles appeared in four different journals with the top three journals being *Desalination*, *Desalination and Water Treatment*, and *International Journal of Water Resources and Development*. The top three institutions with the highest number of publications in this field were KSU, King Abdullah University of Science and Technology, and King Fadh University of Petroleum and Minerals. The papers were cited 18 times; 37.5% of the articles were cited between 1 and 10 times, whereas 62.5% of the articles were never cited. Of the never cited articles, 40% were published in 2013. The two most cited articles were *Seawater desalination in Saudi Arabia: economic review and demand projections* by Al-Sahlawi [23] with 13 citations and *The continued challenge of capacity building in desalination* by Al-Mutaz [3] with 4 citations.

4.6. Other systems

As the number of publications in "Ion Exchange", "Geothermal Desalination", "Wind Desalination", "Adsorption Desalination", "Nuclear Desalination" and "PV/CSP Desalination" were not high, the results were presented as "other systems". There are 73 articles in this category with contributions from 238 authors between 1997 and 2013 (Table 3). Classification of the publications according to the descriptors showed that 54.8% were experimental studies, while 45.2% were theoretical/numerical/simulation studies. Single authorship accounted for 4.2%, while double authorship accounted for 10.0%. The articles appeared in 10 different journals with the top 3 being *Desalination*, *Desalination and Water Treatment*, and *Renewable & Sustainable Energy Reviews*. The top 3 institutions were KFUPM, KSU and SWCC. The articles were cited 533 times with 72.6% of the articles cited between 1 and 10 times and 27.4% never cited. Of the 27.4% never cited, 40% were 2013 publications.

5. Conclusions

This work has investigated research contributions of Saudi universities and institutions in the development of desalination technology. This work is not a full reflection of the Saudi desalination industry, one of the largest of its kind in the world, but the work investigates contributions made by Saudi universities to desalination in the country using only articles features in the ISI database. There is a gap between the Saudi desalination industry interest and research in the universities. The desalination industry in Saudi focuses on the distillation techniques (MSF and MED), while most of the research in the universities is focused on membrane technologies and solar desalination. However, the world's attention is on the university research areas of membrane and renewable energy integration in desalination to offset the heavy use of fossil fuel. This work analyzed a total of 255 articles published in the ISI Web of Science to identify top research universities, top funding agencies, top journals where Saudi researchers published and authors with top publications. The work identified a total of 31 funding agencies (Table 6), with

Table 6
List of funding agencies

Funding agencies	No. of funded research
1. King Abdullah University of Science and Technology (KAUST)	7
2. King Fahd University of Petroleumand Minerals (KFUPM)	17
3. King Saud University	10
4. International Fulbright Science Technology Award US Department of State	3
5. Ministere de l'enseignement superieure et de la recherche scientifique	3
6. Natural Science and Engineering Research	
7. Council of Canada (NSER)	2
8. Saudi Aramco	2
9. Singapore Economic Development Board	2
10. World Class University (WCU) Projects of the National Research Foundation, Korea	4
11. Agence Nationale pour la maîtrise de l'energie	1
12. Center for Clean Water and Clean Energy, MIT	13
13. Cyprus Institute	1
14. Defense Research Development Organization Government of India	1
15. European Union	2
16. E.W.I	1
17. GS E&C, South Korea	1
18. King Abdulaziz City for Science and Technology	3
19. Lebanese National Council for Scientific Research	1
20. Martin Family Foundation	1
21. Middle East Desalination Research Centre	2
22. National Plan for Science and Technology	2
23. National Research Centre, Cairo, Egypt	2
24. National Research Foundation, Singapore	2
25. National University of Singapore	3
26. NED University of Engineering & Technology, Karachi, Pakistan	1
27. Saudi Society of Agricultural Science	1
28. WDRC Group	1
29. University of Malaysia, Pahang Kuantan, Malaysia	1
30. Sultan Qaboos University	1
31. SenterNovem in the framework of the innovator grants	2

KFUPM, Center for Clean Water and Clean Energy, MIT and KSU being the top 3 funding agencies according to this investigation. The top publishing universities are also the top funding agencies (Table 6 and Fig. 8). The work revealed the research trends over the period of two decades. The research output of the top universities, KSU, KFUPM, KAU and KAUST, in desalination are influenced greatly by specialized research chairs and centers for desalination such as Power Chair for Water Research (ACWA-KSU), Renewable and Sustainable Energy Centre (SET-KSU), UNESCO funds for water desalination chair (UNESCO-KSU), Water Desalination and Reuse Center (WDRC-KAUST), Center for Clean Water and Clean Energy (CCWCE-KFUPM), Center of Excellence in Desalination Technology (CEDT-KAU) and the Water Research Center (WRS-KAU). The study confirms that literature on desalination have increased substantially since 1997 when the first article was published. Although, in all the 255 articles analyzed, there was no substantial research work on the reduction of environmental problems associated with brine disposal, the author could not arrived at any cogent reason for this gap in the research.

Additionally, the study provides a platform for both the researcher and government agencies responsible for desalination to be able to assess the past and predict future research direction as concerning desalination.

In addition, the work identified some gaps in research on desalination. Research interest on the coupling of the old MSF systems with renewable energy sources is expected to save the environment from CO_2 as a result of burning fossil fuel. Desalination is a mature technology for water purification, yet there are new developments that reduces the cost of water production. One major future direction is to integrate these new developments in managing cost of distilled water in Saudi. The Saudi populace are not paying the premium for the desalinated water due to government subsidy; research in this direction will condense the subsidy burden on the government. Innovative research toward reduction in desalination energy requirements will help reduce the cost of desalinated water. The innovative research should focus on the development of models and systems to optimally integrate all available energy resources in Saudi for desalination purposes.

One other area that requires study is the manufacturing materials for desalination plants. Current effort in this area is minimum; the universities should lead research in the design and developments of improved materials that will tolerate, in long term, the seawater conditions. This will reduce investment costs in desalination plants, translating to reduced cost of desalinated water.

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