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Global trends and performances of desalination research

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ABSTRACT

This study was designed to evaluate the global scientific output of desalination research to assess the characteristics of the research tendencies and the research performances. Data were based on the online version of *Science Citation Index*, *Web of Science* from 1991 to 2008. Two main respects of the paper characteristics, performance of publication and research tendency, were analyzed. Performances of publications were assessed including document type, language, subject categories, journals, institutes, and countries. Research tendency was investigated by statistically analyzing the distribution of word in article title, author keyword, and keyword plus in different periods. Results show the desalination research mainly performed on subject category of chemical engineering. More specific, research might focus on membranes related research.

Keywords: Bibliometric; *Web of Science*; Desalination; Reverse osmosis; Membrane desalination; Solar energy

1. Introduction

Desalination has long been investigated. In earlier years, distillation of chlorine water [1], the purification of water by continuous fractional distillation [2], the continuous fractional distillation of water [3], and the functional distillation of water vapour [4] were studied. In 1950, researches on scale control in seawater distillation equipment [5], separation of acetic acid and water by distillation [6], fresh water from seawater by solar distillation [7], an all-glass, automatic, water distillation apparatus [8] and solar distillation of salt water in plastic tubes using a flowing stream [9] were presented. Subsequently, more researches concerned seawater desalination, especially using reverse osmosis, were reported in earlier years [10–15] and recently [16–22].

The role of desalination, which produces fresh water from seawater or blackish water, is increasing since the amount of the fresh water is rapidly decreasing because of pollution of water sources such as rivers and lakes caused by rapid development of industry and agriculture, while demand for the fresh water is growing especially in developing countries because of rapid increase in population and improvement of life style in such countries. The three most commercially important technologies are reverse osmosis (RO) [16,17,21], multi-stage flash (MSF) [23–25], and multiple-effect distillation (MED) [26–28]. Moreover other desalination technologies, for example, freezing [29–31], solar distillation [32–34], and electrodialysis [35–38] were also considered.

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Despite the role of desalination have been rapidly growing in 21st century, there have been few attempts at gathering systematic data on desalination research. A common research tool for this analysis is the bibliometric methods which have already been widely applied for the scientific production and research trends in many disciplines of science and engineering [39–41]. Furthermore, the *Science Citation Index* (*SCI*), from the Institute for Scientific Information (ISI), *Web of Science* databases are the most frequently used source database of choice for a broad review of scientific accomplishment in all studying fields [42,43]. Conventional bibliometric methods often evaluate the research trend by the publication outputs of countries, research institutes, journals, and research fields [44–46] or by the citation analysis [47,48]. However, merely depending on the change in the citations or publication counts of countries and organizations cannot completely indicate the development trend or future orientation of the research field.

The keyword plus in the *SCI* database supplied additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes [49]. In recent years, distribution of author keywords in adsorption technology in environmental science [50] and stroke-related research in Taiwan was considered for research trend [51]. Using distributions of words in article title, author keyword, keyword plus, and words in abstracts in different periods were applied to evaluate research trends included the world aerosol [52], stem cell [53], and volatile organic compounds [54]. Furthermore, the method named "word cluster analysis" was successfully applied to find the hotspots of atmospheric simulation [55] and risk assessment research field [56].

In this study, a bibliometric method, analysis of basic publication items such as language, article country, article institute, and journals and their subject category to describe the performance in desalination research was used. Distribution of article title, author keyword, and keyword plus in different periods was used for mapping the trends of global desalination research during the period of 1991–2008 [52]. Findings from these investigations can be information to realize the desalination research and to establish further research directions.

2. Methodology

The data were from the online version of *SCI*, *Web of Science*. According to *Journal Citation Reports* (*JCR*), it indexed 6,620 major journals with citation references across 173 scientific disciplines in 2008. The online version of *SCI* was searched under the keywords (desalination or distillation) and (water* or seawater) as a part of title, abstract, author keywords, and keywords plus to compile a bibliography of all papers related on desalination research. Document information included names of authors, contact address, title, year of publication, author keywords, keywords plus, subject categories, and names of journals publishing the articles. The records were downloaded into Microsoft Excel software, and additional coding was manually performed for the number of origin country and institute of the collaborators, and impact factors of the publishing journals. Impact factors were taken from the *Journal Citation Report* (*JCR*) published in 2008. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as from the United Kingdom (UK). Articles from Hong Kong were not included in China. Contributions of different institutes and countries were estimated by the affiliation of at least one author to the publications. Collaboration type was determined by the addresses of the authors, where the term "single country article" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from multiple countries. The term "single institute article" was assigned if the researchers' addresses were from the same institute. The term "inter-institutionally collaborative article" was assigned if authors were from different institutes. All the articles referring to the desalination research during the past 18 years (1991–2008) were assessed by following aspects: document type and language of publication, characteristics of publication outputs, distribution of output in journals, publication outputs of article country, article institute, and analysis of words in title, author keywords, and keywords plus. Keywords were defined as comma-separated items of one or more words. All keywords, both those reported by authors and those attributed by ISI, as well as words in title were identified and separated into 6-year span (1991–1996, 1997–2002, and 2003–2008), then their ranks and frequencies were calculated.

3. Results and discussion

3.1. Document type and language of publication

The distribution of the document type identified by ISI was analyzed. There were 4,836 publications with 10 document types indexed in the SCI, which included 3,223 publications of article. Article, as the most popular document type, comprises 67% of the total production and was followed distantly by proceedings papers (1,427, 30%). The others showing less significance were reviews (88), notes (29), editorial materials (27), new items (24), meeting abstracts (9), letters (7), correction (1), and reprint (1). As the journal article was dominant in the document types and were also peer-reviewed within this field, they were identified and further analyzed. There are 3,223 articles with 13 languages used. English, as the most popular language, comprises 94% of the total articles and was followed distantly by Japanese (57; 1.8%). Some other languages that were less used on were as follows: French (30), Chinese (25), Polish (20), and German (20). Still some

other languages generally less performed in were Russian (8), Spanish (7), Rumanian (6), Portuguese (5), Czech (2), and one for Korean and Hungarian respectively.

3.2. Trend of publication

The total amounts of *SCI* journals' publications including searching words (desalination or distillation) and (water* or seawater) since 1900 were counted and displayed in Fig. 1. A development trend was found for all documents and articles, searched by title, keyword, and abstract, increase from one in 1903 to 537 publications in all documents in 2008, and one in 1903 to 372 articles in 2008. According to a limitation of the *Science Citation Index* database, since 1991, abstract information has been included in it. The topic search can trace the related information in title, abstract, and keywords at the same time. Searching keywords in title only is necessary to obtain a reasonable base for an earlier starting year before 1991. A similar trend was also appeared for all documents and articles, searched by title only, increase from one in 1903 to 65 publications in all documents in 2008, and one in 1903 to 39 articles in 2008. In earlier years, few articles were reported in 1900s and 1910s included the distillation of chlorine water [1], the purification of water by continuous fractional distillation [2], the continuous fractional distillation of water [3], the functional distillation of water vapour [4], the distillation of cooling water in power stations [57], and the laboratory device for water vapour distillation in vacuum [58]. In 1940's, water vapour distillation was reported [59]. Several desalination related topic were also presented in the same period, for example, an arrangement by which a single water tap may be used to run [60], trap for determination of water by the distillation method [61], and fractional distillation of multicomponent mixtures [62]. An increasing appeared in 1960's, throughput consumption for water desalination by electrodialysis was reported [63]. In the following years, demineralization of saline water [64], automatic distiller for the primary distillation of water [65], solar water distillation in North-India [66], distillation processes for saline water conversion [67], and production of fresh water from seawater without metallic transfer surfaces [68]. After 1990, a sharply increasing was found. This period would be focused in this study. Built on many breakthroughs in the study period during 1991 to 2008, desalination research has became one of the most important and dynamic field of human research [69–71].

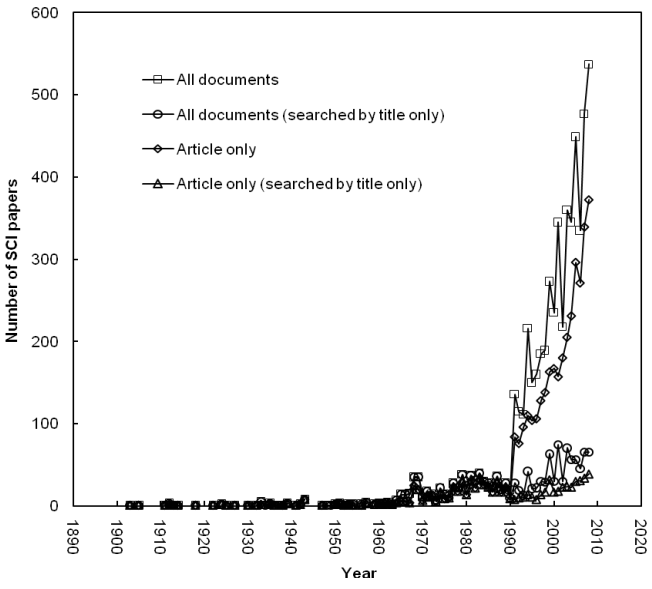

Fig. 1. Number of *SCI* journal publications referring to keywords (desalination or distillation) and (water* or seawater) in the last 100 years.

3.3. Distribution of output in subject categories and journals

Based on the classification of subject categories in *JCR* in 2008, the publication output data was distributed in 130 *SCI* subject categories. The top twenty productive subject categories are shown in Table 1. Subject categories containing at least 300 articles were chemical engineering (1,548; 48%), water resources (669; 21%), and energy and fuels (319; 10%). Sixty-nine percent of journals listed in both the subject categories of chemical engineering and water resources published desalination articles. Fig. 2 shows trends of top five productive subject categories. Articles published in the category of chemical engineering increased and reached to a plateau after 2005. A similar trend was also appeared in the category of water resources.

In total, 3,223 articles were published in a wide range of 705 journals which all belong to 130 *SCI* subject categories. Bradford's Law of Scattering [73] was applied. Bradford's law was used to estimate the exponentially diminishing returns of extending a search for references in science journals. One formulation of Bradford's law is that if journals in a field are sorted by number of articles into three zones, each with about one-third of all articles, then the number of journals in each zone will be proportional to $1 : n : n^2$. The journals of zone 1 could be recognized as the core journals obviously. The journals in descending order in terms of their published articles, and the journals were divided into three "zones". Zone 1, representing the most productive third of the total articles, contained 8 journals or 1.1% of 705 journals. Zone 2, representing the next most productive third of total articles, contained 71 journals or 10% of 705 journals. Zone 3, representing the least productive third of total articles, contained 626 journals or 89% of 705 journals. The number of journals of three zones approximately followed the Bradford's law. To reiterate, the number of journals was approximate $1 : n : n^2$ (1.0 : 8.9 : 78). Table 2 showed 8 core journals with the respective IF, ISI category of the journal, position of

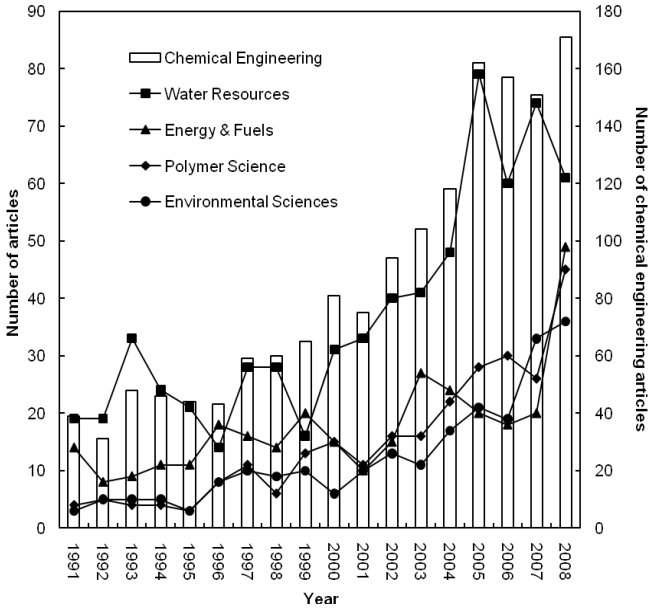

Fig. 2. Comparison the growth trends of the top five productive subject categories.

the journal in its category in 2008, number of relevant articles, and the percentage of total articles. *Desalination* ranked first with 521 (16%) published articles followed by *Journal of Membrane Science* with 192 articles; while *Journal of Membrane Science* and *Separation and Purification Technology* had a relatively higher impact factors. Six journals were listed in subject category of chemical engineering. In addition, as regards to the impact factor for all journals, *Nature* won the first place with the highest impact factor (31.434) with 2 articles, followed by *Nature Nanotechnology* (IF = 20.571) with 2 articles.

3.4. Performance of countries and institutes

The contribution of different countries/territories was estimated by the location of the affiliation of at least one author of the published articles. There were 40 (1.2%) articles without author address information in the ISI, *Web of Science* and these were excluded. Table 3 shows the top 20 countries ranked by the number of total articles, including the number of single country articles, internationally collaborative articles, first author articles, corresponding author articles, as well as the percentage of collaborative articles in total articles for each country and number of average author of single country articles. Of all the 3,183 articles with author addressed in ISI, 2,689 (84%) were single country articles and 494 (16%) were internationally collaborative articles. The USA ranked top

Table 1
Top 20 productive subject categories of desalination articles

SCI subject category	TP	%	NJA	TP/NJA	NJ	%NJA
Chemical Engineering	1,548	48	82	19	116	71
Water Resources	669	21	37	18	60	62
Energy & Fuels	319	10	42	8	67	63
Polymer Science	267	8.3	29	9	73	40
Environmental Sciences	224	7.0	70	3	163	43
Multidisciplinary Chemistry	219	6.8	51	4	127	40
Food Science & Technology	211	6.5	50	4	107	47
Analytical Chemistry	193	6.0	48	4	70	69
Thermodynamics	188	5.8	21	9	44	48
Applied Chemistry	185	5.7	35	5	61	57
Physical Chemistry	135	4.2	47	3	113	42
Environmental Engineering	116	3.6	27	4	38	71
Mechanics	110	3.4	14	8	112	13
Civil Engineering	84	2.6	18	5	91	20
Biotechnology & Applied Microbiology	76	2.4	31	2	144	22
Nuclear Science & Technology	72	2.2	21	3	30	70
Mechanical Engineering	70	2.2	16	4	105	15
Nuclear Physics	55	1.7	3	18	20	15
Multidisciplinary Agriculture	50	1.6	8	6	35	23
Biochemical Research Methods	49	1.5	10	5	65	15

TP: Number of articles; %: the percentage of articles from different subject categories in total publications; NJA: number of journals published desalination articles; NJ: number of journals in a subject category; %NJA: the percentage of journals published desalination articles in subject category

Table 2
The 8 Bradford's core journals with the number of article, impact factor, ISI category of journals, and the position of the journal in its category

Journal title	TP (%)	IF	ISI Subject category	Position
Desalination	521 (16)	1.155	Chemical engineering Water resources	44/116 26/60
Journal of Membrane Science	192 (6.0)	3.247	Chemical rngineering Polymer science	4/116 11/73
Industrial & Engineering Chemistry Research	137 (4.3)	1.895	Chemical engineering	22/116
Energy Conversion and Management	53 (1.6)	1.813	Thermodynamics Energy and fuels Mechanics Nuclear physics	6/44 17/67 19/112 10/20
Separation Science and Technology	53 (1.6)	1.139	Multidisciplinary chemistry Chemical engineering	69/127 43/116
Separation and Purification Technology	49 (1.5)	2.503	Chemical engineering	9/116
Chemical Engineering Science	44 (1.4)	1.884	Chemical engineering	24/116
Chemical Engineering Research & Design	42 (1.3)	0.989	Chemical engineering	52/116

TP: Number of articles; %: the percentage of articles in total publications; IF: impact factor

Table 3
The top 20 productive countries ranked by total number of articles

Country	TP	TPR (%)	SPR (%)	CPR (%)	FAR (%)	RPR (%)	%C	SA/SP
USA	572	1 (18)	1 (16)	1 (27)	1 (16)	1 (15)	24	2.9
China	255	2 (8.0)	2 (7.7)	6 (9.5)	2 (7.3)	2 (7.5)	18	3.8
Japan	231	3 (7.3)	3 (7.5)	11 (6.1)	3 (6.7)	3 (6.6)	13	3.8
Germany	196	4 (6.2)	6 (4.6)	2 (15)	6 (4.7)	6 (4.6)	37	2.9
Spain	191	5 (6.0)	5 (5.9)	8 (6.7)	5 (5.5)	4 (5.4)	17	3.4
India	190	6 (6.0)	4 (6.6)	20 (2.6)	4 (5.9)	5 (5.3)	6.8	3.0
UK	144	7 (4.5)	7 (2.9)	4 (13)	8 (3.2)	7 (3.2)	45	2.7
France	141	8 (4.4)	9 (2.6)	2 (15)	7 (3.3)	7 (3.2)	51	3.5
Canada	121	9 (3.8)	8 (2.6)	5 (10)	9 (2.7)	9 (2.6)	41	3.0
Italy	84	10 (2.6)	14 (2.0)	12 (5.9)	14 (2.0)	13 (2.0)	35	3.8
Poland	81	11 (2.5)	11 (2.4)	16 (3.4)	10 (2.3)	10 (2.4)	21	2.1
Australia	81	11 (2.5)	17 (1.8)	8 (6.7)	13 (2.1)	14 (2.0)	41	2.7
Kuwait	77	13 (2.4)	9 (2.6)	31 (1.6)	11 (2.2)	11 (2.3)	10	2.7
Jordan	74	14 (2.3)	20 (1.5)	7 (6.9)	15 (1.9)	15 (1.9)	46	2.4
Taiwan	69	15 (2.2)	12 (2.3)	31 (1.6)	12 (2.1)	12 (2.1)	12	3.2
Israel	68	16 (2.1)	16 (1.9)	14 (3.6)	16 (1.8)	17 (1.8)	26	2.8
Netherlands	65	17 (2.0)	25 (1.3)	10 (6.3)	19 (1.6)	20 (1.7)	48	3.5
Saudi Arabia	65	17 (2.0)	13 (2.1)	28 (1.8)	16 (1.8)	15 (1.9)	14	2.3
Russia	62	19 (1.9)	15 (1.9)	24 (2.2)	18 (1.8)	17 (1.8)	18	3.1
United Arab Emirates	58	20 (1.8)	19 (1.6)	19 (3.0)	19 (1.6)	21 (1.6)	26	2.1

TP: number of total articles; TPR (%), SPR (%), CPR (%), FAR (%), RPR (%): rank and percentage of total articles, single country articles, internationally collaborative articles, first author articles, corresponding author articles in their total articles; %C: country collaboration ratio, the percentage of collaborative articles in total articles for each country; SA/SP: number of average author of single country articles.

one on all indicators, such as total (18%), single country (16%), internationally collaborative (27%), first author (16%), and corresponding author articles (15%). Single-country articles were authored by 87 different countries. Twenty-three countries contributed only one or two single-country articles, and 27 countries contributed only one or two internationally collaborative articles. Table 3 shows that France (51%), Netherlands (48%), Jordan (46%), and UK (45%) had a relative high percentage of internationally collaborative articles (%C). It also appears that India (6.8%) was more inclined or able to conduct research independently. The lowest average number of authors per single country article (SA/SP) was found to be 2.1 authors per article for United Arab Emirates and Poland, respectively. However China, Italy, and Japan had higher value of 3.8 respectively.

Comparison of the growth trends of the top six most productive countries is displayed in Fig. 3, and that of BRIC is shown in Fig. 4. BRIC, Brazil, Russia, India, and China had the fastest growing economies in the world, and it was predicted that in less than forty years, the BRIC economies collectively will be larger than the USA, Japan, the UK, Germany, France and Italy [73]. Publications from China and India grew sharply, while those of Russia and Brazil increased slowly during 1991–2008, which might be evidence of the remarkable differences in their development of technologies. In 1997, when the National Basic Research Program (also called the 973 Program) was approved by the Chinese government (www.973.gov.cn), publications from China started growing. After 2004, publications for China had a higher growth rate than others, and quickly closed to the top one country of the USA. There was no doubt that a series of positive policies motivated the rapid development of research in China. A similar result was also found in the case of atmospheric simulation research [55].

The performances of different institutes were estimated by the affiliation of at least one author. Of the 3,183 articles with author addresses, 2,018 (63%) were single institute articles and 1,165 (37%) were inter-institutionally collaborative articles. Among the top 10 institutes, 3 (27%) were in China and 2 were in Kuwait. However, a bias appeared because the Indian Institute of Technology and the Chinese Academy of Sciences have branches in many different cities [55]. At present, the articles of these two institutes were pooled as one heading, and articles divided into branches would result in different rankings. Thus, leading was Kuwait University at Kuwait, the university published the most of total, single institute, first author, and corresponding author articles (Table 4). Kuwait University had low percent of inter-institutionally collaborative articles and percentage of inter-institutionally collaborative publications in total institute publications (24%). The results demonstrating Kuwait University strongly independent research ability and less desire to collaborative with other institutes in desalination research.

3.5. Distribution of words in article title, author keywords, and keywords plus

The title of an article includes words which the authors express as the most important essence from his research work. Author keywords analysis could offer the informa-

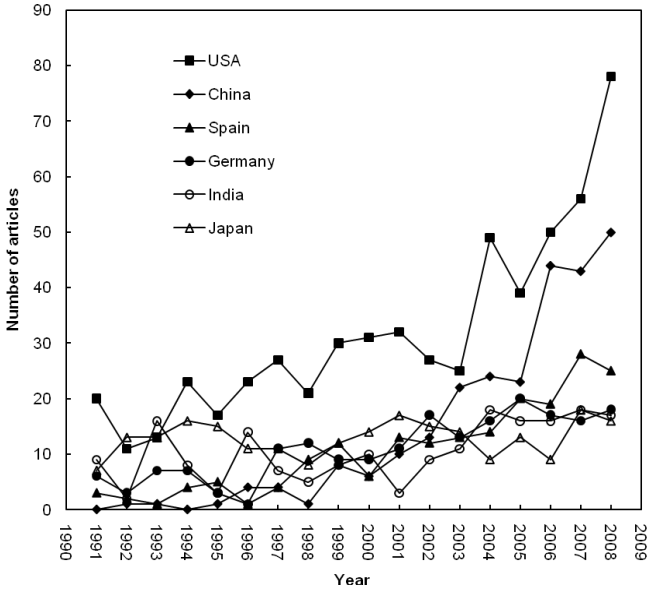

Fig. 3. Comparison the growth trends of the top six most productive countries during the last 18 years.

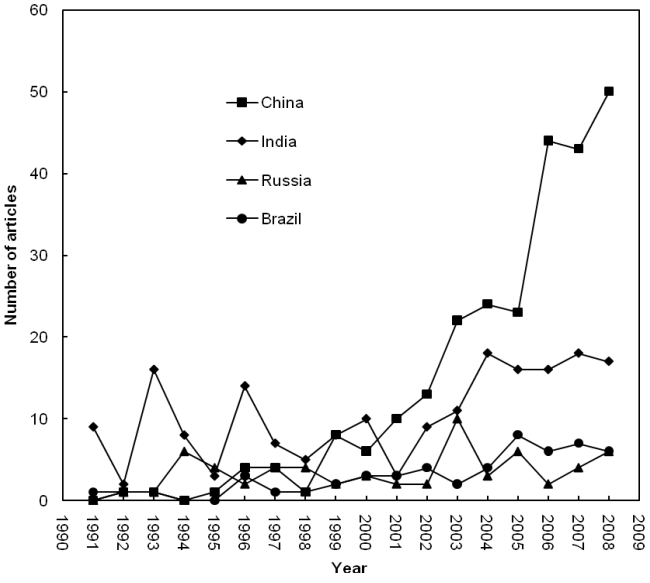

Fig. 4. Comparison the growth trends of the BRIC during the last 18 years.

Table 4
The top 10 most productive institutes of desalination, including the ranking and respective percentages of publications, independent publications, inter-institutionally collaborative publications, first author, and corresponding author publications

Institute	TP	TPR (%)	IPR (%)	CPR (%)	FPR (%)	RPR (%)	%C
Indian Institute of Technology, India	66	1 (2.1)	1 (2.4)	3 (1.5)	1 (2.0)	1 (1.8)	27
Kuwait University, Kuwait	49	2 (1.5)	2 (1.8)	7 (1.0)	2 (1.4)	2 (1.4)	24
Chinese Academy of Sciences, China	39	3 (1.2)	18 (0.59)	1 (2.3)	8 (0.63)	8 (0.66)	69
Jordan University of Science and Technology, Jordan	38	4 (1.2)	11 (0.69)	2 (2.1)	4 (0.91)	4 (1.0)	63
Szczecin University of Technology, Poland	33	5 (1.0)	3 (1.4)	89 (0.34)	3 (0.94)	3 (1.0)	12
Tsing Hua University, China	32	6 (1.0)	5 (1.0)	7 (1.0)	6 (0.79)	7 (0.79)	38
National University of Singapore, Singapore	30	7 (0.94)	8 (0.79)	5 (1.2)	5 (0.82)	5 (0.83)	47
Kuwait Institute for Scientific Research, Kuwait	27	8 (0.85)	4 (1.2)	137 (0.26)	7 (0.75)	5 (0.83)	11
Beijing University of Chemical Technology, China	24	9 (0.75)	11 (0.69)	14 (0.86)	8 (0.63)	8 (0.66)	42
University of New South Wales, Australia	23	10 (0.72)	33 (0.40)	4 (1.3)	14 (0.50)	24 (0.40)	65
Sultan Qaboos Uinversity, Oman	23	10 (0.72)	19 (0.50)	6 (1.1)	14 (0.50)	14 (0.50)	57

TP, total articles; TPR, total articles rank; IPR, independent article rank; CPR, inter-institutionally collaborative article rank; FPR, first author article rank; RPR, corresponding author article rank; % share in their total articles; %C percentage of inter-institutionally collaborative articles in total institute articles.

tion of research trends as viewed by researchers [52,53]. Keywords plus provided search terms extracted from the titles of papers cited in each new article in the database in ISI [49]. In recent years, using results of distributions of words in article title and abstract, author keywords, and keywords plus in different periods were presented to evaluate research treads [52–54]. There were 3,223; 2,202; and 2,339 articles with title, author keywords, and keyword plus information respectively. Thus, not all articles were analyzed for these words. All the single words in the titles of articles were statistically analyzed. As a result, 30 most frequently used substantives in article titles are shown in Table 5 in 3 six-year periods. Some words have no usefulness for the analysis of research trend such as prepositions, articles, conjunctions, and common words such as "using" and "study" were discarded in this analysis. Except for "water", "distillation", and "desalination" which were searching words, "membrane", "process", and "solar" were the most frequently used single words in article titles. "Osmosis", "reverse", "oil", "seawater", "experimental", "acid", "essential", "energy", and "mass" in article titles had a notable increasing trend. However, the words "determination", "effect", "plant", and "plants" in title showed a decrease during the study period.

The analysis of author keywords revealed that 6,058 author keywords were used from 1991 to 2008. Table 6 shows the 30 most frequently used author keywords with their rankings and percentages. The most frequently used author keywords were "reverse osmosis", "membrane distillation", and "solar energy". "Electrodialysis", "simulation", "seawater desalination", "essential oil", "solar desalination", "ethanol", "modeling", "essential oil composition", "nanofiltration", "seawater", "fouling", "optimization", "membrane", and "concentration polarization" had higher increasing rates in the ranking of frequencyKeywords plus were analyzed to substantially augment author-keyword and title-word indexing. Table 7 shows distributions of the top 30 most used keywords plus. "Pervaporation", "simulation", "seawater desalination", "ethanol", "optimization", and "membranes" listed in the top 30 of keywords plus also appeared in the top 30 of author keywords. Again, "seawater desalination", "membranes", and "system" exhibited their rapid growing pace on desalination research.

3.6. Hot issues

In order to overcome the weak points of the three separated types of keywords analysis, the words in article title, author keywords, and keywords plus were combined, then synonymic single words and congeneric phrases were summed into categories, so as to analyze the historical development of the science more completely and precisely, and more importantly, to discover the directions the science is taking. Research trends in desalination were extracted and separated into three topics: membrane desalination, MSF (multi-stage flash) desalination, and solar desalination. The topic membrane included the words "membrane", "membranes" and "osmosis", the topic MSF included the words "MSF" and "flash", and the topic solar included only word "solar". MSF desalination and membrane desalination are the two most important technologies which have been commercially succeeding. At the end of 2002, MSF and membrane desalination accounted for 36.5% and 47.2%, respectively of the installed brackish and seawater desalination capacity. For seawater

Table 5
Top 30 most frequency substantives in article titles during 1991–2008 and 3 six-year periods

Words in title	TP	91–08 R (%)	91–96 R (%)	97–02 R (%)	03–08 R (%)
Water	642	1 (20)	1 (17)	2 (20)	1 (21)
Distillation	630	2 (20)	3 (17)	1 (22)	2 (19)
Desalination	529	3 (16)	1 (17)	3 (17)	3 (16)
Membrane	307	4 (9.5)	4 (8.2)	4 (9.6)	4 (9.9)
Process	217	5 (6.7)	9 (5.0)	6 (5.8)	5 (7.8)
Solar	210	6 (6.5)	6 (5.9)	5 (6.5)	7 (6.7)
Analysis	198	7 (6.1)	5 (6.1)	7 (5.7)	9 (6.4)
System	197	8 (6.1)	6 (5.9)	8 (5.6)	8 (6.5)
Osmosis	168	9 (5.2)	158 (0.69)	10 (4.8)	6 (6.9)
Reverse	152	10 (4.7)	158 (0.69)	11 (4.7)	10 (6.1)
Membranes	151	11 (4.7)	11 (4.7)	19 (3.4)	11 (5.4)
Determination	138	12 (4.3)	8 (5.2)	9 (5.1)	21 (3.5)
Oil	131	13 (4.1)	24 (2.6)	15 (3.8)	12 (4.7)
Production	131	13 (4.1)	16 (3.3)	18 (3.5)	13 (4.6)
Seawater	129	15 (4.0)	20 (2.8)	13 (3.9)	14 (4.5)
Separation	128	16 (4.0)	12 (3.8)	21 (3.3)	15 (4.4)
Effect	126	17 (3.9)	9 (5.0)	15 (3.8)	19 (3.6)
Performance	126	17 (3.9)	15 (3.5)	21 (3.3)	15 (4.4)
Plant	118	19 (3.7)	12 (3.8)	12 (4.0)	22 (3.4)
Systems	107	20 (3.3)	20 (2.8)	17 (3.6)	24 (3.3)
Design	105	21 (3.3)	20 (2.8)	42 (2.3)	17 (4.0)
Experimental	97	22 (3.0)	91 (1.0)	19 (3.4)	22 (3.4)
Extraction	96	23 (3.0)	26 (2.4)	24 (3.2)	26 (3.0)
Acid	94	24 (2.9)	215 (0.52)	24 (3.2)	20 (3.6)
Essential	92	25 (2.9)	120 (0.87)	48 (2.0)	17 (4.0)
Energy	92	25 (2.9)	52 (1.6)	28 (2.9)	25 (3.3)
Plants	91	27 (2.8)	17 (3.1)	21 (3.3)	35 (2.5)
Mass	86	28 (2.7)	158 (0.69)	24 (3.2)	26 (3.0)
Heat	84	29 (2.6)	43 (1.7)	30 (2.8)	29 (2.8)

TP: the number of total articles; R (%): the rank and percentage of word in article titles in total articles.

desalination, MSF and membrane desalination accounted for 61.6% and 26.7% respectively [74]. Solar desalination is the one of the oldest technologies among the various types of desalination technologies, and has been widely studied. Solar energy is free and clean energy which can be obtained anywhere in the world. Solar desalination can be the alternative desalination methods as small-scale, self-reliant fresh water source, especially in the areas that are unable to afford MSF and membrane desalination as a fresh water source because of their desalination costs still remain high even today [75].

Fig. 5 shows the research trends for the topics of "membrane", "solar", and "MSF" desalination from year 1991 to 2008. The number of articles related membrane increased rapidly from the middle of 1990s, while one related MSF increased slower or kept the same level. This is because that studies on MSF desalination had been done earlier than membrane desalination, and a great deal of progress on MSF desalination has been made in the last 30 years, while membrane desalination technology is new technology compared with MSF desalination, and a lot of improvements have been made in the reverse osmosis process in the last 20 years [74]. There were many kinds of progress for MSF desalination research, such as equipment design and configuration, thermodynamic design, material selection and structural aspects, vertical MSF, chemical treatment, as well as control and instrumentation, while in membrane desalination most of progress has been made through improvements in membrane themselves, which included better resistance to compression, longer life, higher possible recovery, improved flux, and improved salt passage [74]. MSF desalination occupies large share in seawater desalination plants today. However membrane desalination has been

Table 6
Top 30 frequency of author keywords used

Author keywords	TP	91–08 R (%)	91–96 R (%)	97–02 R (%)	03–08 R (%)
Desalination	312	1 (14)	2 (8.9)	1 (14)	1 (15)
Reverse osmosis	166	2 (7.5)	3 (5.3)	2 (8.2)	2 (7.6)
Distillation	142	3 (6.4)	1 (14)	3 (5.8)	3 (5.5)
Membrane distillation	111	4 (5.0)	8 (3.1)	4 (5.0)	4 (5.4)
Solar energy	62	5 (2.8)	4 (4.9)	5 (4.2)	13 (1.8)
Pervaporation	53	6 (2.4)	6 (4.4)	10 (2.4)	10 (2.1)
Water	51	7 (2.3)	8 (3.1)	19 (1.6)	6 (2.5)
Solar distillation	49	8 (2.2)	4 (4.9)	21 (1.4)	9 (2.1)
Solar still	49	8 (2.2)	7 (4.0)	10 (2.4)	13 (1.8)
Electrodialysis	48	10 (2.2)	N/A	7 (2.9)	8 (2.2)
Simulation	47	11 (2.1)	35 (0.89)	6 (3.2)	13 (1.8)
Seawater desalination	45	12 (2.0)	N/A	8 (2.7)	10 (2.1)
Essential oil	45	12 (2.0)	14 (1.8)	35 (1.0)	5 (2.6)
Solar desalination	45	12 (2.0)	23 (1.3)	19 (1.6)	7 (2.4)
Mass transfer	41	15 (1.9)	13 (2.2)	12 (2.1)	18 (1.7)
Ethanol	40	16 (1.8)	8 (3.1)	17 (1.8)	19 (1.6)
Modeling	37	17 (1.7)	95 (0.44)	14 (1.9)	17 (1.8)
Extractive distillation	36	18 (1.6)	23 (1.3)	14 (1.9)	21 (1.6)
Essential oil composition	34	19 (1.5)	N/A	21 (1.4)	13 (1.8)
Nanofiltration	33	20 (1.5)	N/A	48 (0.80)	10 (2.1)
Water desalination	33	20 (1.5)	14 (1.8)	9 (2.6)	34 (1.0)
Seawater	30	22 (1.4)	95 (0.44)	14 (1.9)	25 (1.3)
Fouling	29	23 (1.3)	N/A	27 (1.1)	19 (1.6)
Brackish water	28	24 (1.3)	95 (0.44)	17 (1.8)	31 (1.2)
Optimization	27	25 (1.2)	N/A	27 (1.1)	22 (1.5)
Membranes	27	25 (1.2)	35 (0.89)	12 (2.1)	35 (0.89)
Reactive distillation	26	27 (1.2)	35 (0.89)	27 (1.1)	25 (1.3)
Water treatment	25	28 (1.1)	23 (1.3)	61 (0.64)	23 (1.3)
Membrane	24	29 (1.1)	95 (0.44)	48 (0.80)	23 (1.3)
Concentration polarization	23	30 (1.0)	95 (0.44)	48 (0.80)	25 (1.3)

TP: articles in the study period; R (%): the rank and percentage of the author keyword

growing rapidly in recent years, and will become cost competitive. A lot of studies on membrane desalination, especially membrane themselves, will be done in the future, while main technique for MSF desalination have been established and the research topics for MSF will be on energy source, scaling and fouling, materials, optimization and improvement of the process. Therefore, it is expected that research on membrane desalination will grow constantly in the next decades, while one on MSF desalination will increase slightly or reaches to plateau. The solar desalination can be used as a fresh water sources for remote settlements where salty water is the only type of moisture available, power is scarce and demand is less than 200 m^3/d, since other desalination plants are uneconomical for low-capacity fresh water demand, setting of water pipelines for such area is uneconomical, and delivering water by tracks or ships is unreliable and expensive [75]. Further, in the future, global warming and a shortage of fossil fuel will be the greatest problems for human kind, the role of solar desalination which uses clean and renewable energy will increase. Therefore, the number of studies on solar desalination for large-scale plants which are mainly attained by indirect solar desalination such as multistage flash desalination, vapor compression, and reverse osmosis with solar collectors for heat generation, as well as for small-scale plants which are mainly attained by direct solar desalination which uses solar energy to produce distillate directly in the solar collector [76], will increase constantly in the future.

Table 7
Top 30 frequency of keywords plus used

Keywords plus	TP	91–08 R (%)	91–96 R (%)	97–02 R (%)	03–08 R (%)
Water	348	1 (15)	1 (10)	1 (17)	1 (15)
Distillation	190	2 (8.1)	2 (6.1)	2 (9.0)	3 (8.2)
Desalination	157	3 (6.7)	3 (3.7)	13 (2.4)	2 (9.3)
Performance	128	4 (5.5)	3 (3.7)	7 (3.6)	4 (6.7)
Systems	128	4 (5.5)	3 (3.7)	6 (4.4)	5 (6.3)
Separation	121	6 (5.2)	10 (2.7)	3 (7.1)	7 (4.8)
Design	108	7 (4.6)	7 (3.0)	5 (4.6)	6 (5.0)
Mixtures	90	8 (3.8)	19 (1.4)	4 (4.9)	10 (3.9)
Mass-transfer	83	9 (3.5)	7 (3.0)	15 (2.2)	9 (4.3)
System	78	10 (3.3)	19 (1.4)	17 (2.0)	8 (4.3)
Transport	70	11 (3.0)	3 (3.7)	10 (2.5)	12 (3.1)
Simulation	67	12 (2.9)	19 (1.4)	8 (3.3)	13 (3.0)
Model	61	13 (2.6)	55 (0.68)	9 (2.7)	13 (3.0)
Seawater desalination	59	14 (2.5)	N/A	40 (1.1)	11 (3.7)
Extraction	55	15 (2.4)	10 (2.7)	10 (2.5)	23 (2.2)
Removal	54	16 (2.3)	N/A	13 (2.4)	17 (2.8)
Plants	53	17 (2.3)	12 (2.4)	18 (1.9)	21 (2.4)
Reverse-osmosis	52	18 (2.2)	7 (3.0)	77 (0.63)	17 (2.8)
Optimization	52	18 (2.2)	19 (1.4)	45 (0.94)	13 (3.0)
Energy	49	20 (2.1)	12 (2.4)	40 (1.1)	20 (2.5)
Wastewater	48	21 (2.1)	19 (1.4)	40 (1.1)	19 (2.6)
Recovery	48	21 (2.1)	55 (0.68)	59 (0.79)	16 (2.9)
Heat	47	23 (2.0)	15 (2.0)	23 (1.6)	23 (2.2)
Pervaporation	46	24 (2.0)	17 (1.7)	22 (1.7)	25 (2.1)
Membranes	44	25 (1.9)	140 (0.34)	23 (1.6)	22 (2.3)
Acid	43	26 (1.8)	32 (1.0)	18 (1.9)	26 (2.0)
Gas-chromatography	41	27 (1.8)	15 (2.0)	10 (2.5)	44 (1.3)
Column	40	28 (1.7)	55 (0.68)	23 (1.6)	26 (2.0)
Ethanol	36	29 (1.5)	19 (1.4)	30 (1.4)	32 (1.6)
Prediction	35	30 (1.5)	55 (0.68)	23 (1.6)	32 (1.6)

TP: articles in the study period; R (%): the rank and percentage of the author keyword

4. Conclusions

In this study on desalination publications listed in *SCI*, significant points on worldwide research performance from 1991 to 2008 were obtained. Article was the dominant document type; nine other document types were also used. English was by far the dominant language; while 12 other languages were used as well. There were totally 705 journals listed in the 130 *SCI* subject categories. The highest number of articles was in *Desalination*. The subject category of chemical engineering had the most articles. The USA ranked top one on all indicators, such as total, single country, internationally collaborative, first author, and corresponding author articles. The Kuwait University was the flagship in this field. By synthetically and innovatively analyzing the distribution and changes of words in article title, author keywords, and keywords plus, the development of research on desalination during last decade were described, and the future orientation of desalination research were also predicted. It can be concluded that desalination research related to membranes is major directions of desalination research in the future.

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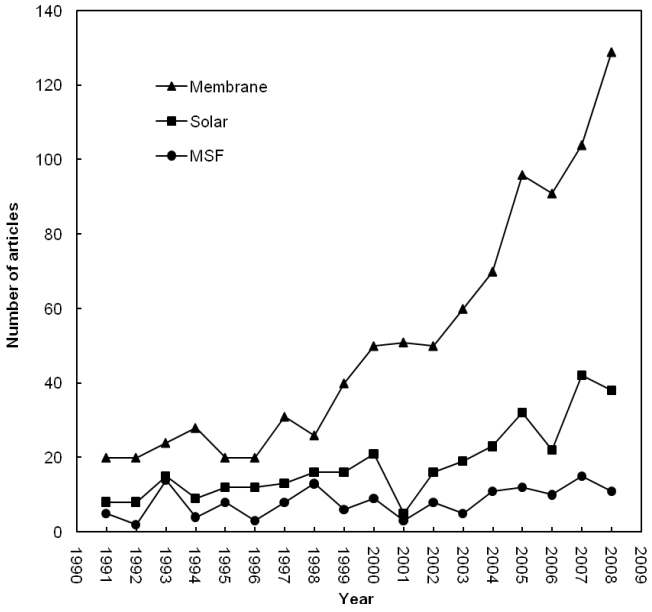

Fig. 5. Comparison of the trends of desalination related items, including MSF, solar, and membrane.

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