Global Trends of Electrodialysis Research during 1991-2014: a Bibliometric Analysis

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(Received on 19th November 2015, accepted in revised form 5th April 2016)

Summary: Electrodialysis is a mass separation process in which electric energy is used as the driving force to remove ionic components from aqueous solutions through ion-exchange membranes. The present research was performed to evaluate the global scientific output of electrodialysis-related research based on the Science Citation Index-Expanded database from 1991 to 2014. The publication characteristics of document types, languages, journals, subject categories, countries, and institutes were identified in electrodialysis field. In addition, author keywords analysis and "word cluster analysis" were applied to give an insight into the research emphases and trends on electrodialysis. The electrodialysis-related research experienced notable increase in the past 24 years. *Desalination* was the most active journal in electrodialysis field, followed by *Journal of membrane science* and *Separation and purification technology.* China and France were the two largest contributors to electrodialysis research. However, their collaboration patterns were different. Research on ion-exchange membranes, especially bipolar membrane, was one of the hotspots in electrodialysis field. Electrodialysis used for desalination and wastewater treatment were the two most frequently studied applications. Other membrane processes such as reverse osmosis, nanofiltration, and ultrafiltration were the most frequent combination technology with electrodialysis.

Keywords: Electrodialysis; Bibliometric analysis; Research trend; Ion-exchange membrane; Science Citation Index- Expanded.

Introduction

Electrodialysis is a mass separation process in which ion-exchange membranes are arranged alternatively in a direct current field to separate ionic species from solvent and other uncharged components. Electrodialysis technology developed along with the progress in researches on ion-exchange membranes (IEMs). The research on IEMs began in 1890 when Ostwald [1] discovered that a semipermeable membrane could be impermeable for any electrolyte if it was impermeable either for its cation or its anion and postulated the existence of the so-called "membrane potential" at the boundary between the membrane and the solution caused by the difference in concentration. Later, Donnan [2] confirmed the existence of such boundary and developed a mathematical equation to describe this concentration equilibrium, which resulted in the so-called "Donnan exclusion potential". In 1920s, researchers spent a lot of effort in studying the physical/chemical properties and transport mechanisms of membranes, and many theories trying to explain the "membrane phenomenon" were proposed. In 1940, Meyer and Strauss [3] proposed a multi-chamber electrodialysis device which had strong practical significance. The preparation of IEM with high selectivity and low resistance by Juda and McRae [4] in 1950 had established the foundation for practical application of electrodialysis technology. Shortly after that, the first commercialized electrodialysis apparatus made by Ionics Inc. appeared. The IEM and electrodialysis had been widely used in many fields since then. In 1970s, desalination of natural water by electrodialysis had become a relatively mature unit operation process. Meanwhile, development of special IEMs, especially bipolar membrane [5], had brought many novelties in electrodialysis applications today. The electrodialysis technology kept ramifying during the past century, resulting in many branch technologies including conventional electrodialysis, electro-electrodialysis, electrodeionization, two-phase electrodialysis, electrometathesis, electrodialysis with bipolar membrane (EDBM), and electro-ion substitution [6, 7]. In recent years, a great deal of work has been dedicated to improve the performance of IEMs and electrodialysis devices and to broaden the applications of electrodialysis. There are some review papers on the development of IEMs [8-10], applications of electrodialysis [7, 11, 12] and applications of EDBM in food industry [13] and environmental protection [14]. However, a comprehensive statistical review of the world electrodialysis related research has not yet been reported to date.

Bibliometric analysis is an effective method to find the research trend of a specific field, and has been broadly applied to analyze the scientific production and research trends in numerous fields,

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such as life cycle assessment [15], pharmaceutical wastewater treatment [16], palm oil sustainability [17], and electrochemical technology for water and wastewater treatment [18]. In this study, a bibliometric analysis was performed on electrodialysis-related research during the period of 1991-2014. Basic publication items including publication outputs, languages, subject categories, journals, countries, and institutes were identified to describe the status of the electrodialysis research. Moreover, “word cluster analysis” was applied to evaluate the research hotspots during 1991-2014. These results could provide information about the current state of electrodialysis research and also help researchers clarifying the future research directions.

Data Sources and Methods

Literatures used in this study were obtained from the online version of Science Citation Index-Expanded (SCIE), Thomson Reuters Web of Science database. Electrodialysis-related articles published during 1991-2014 were retrieved based on the topic (electrodialysis or electro-dialysis or electrodialytic or electrodialyzer*). Since reverse electrodialysis is a technology to derive energy from the difference between chemical potentials of concentrated and diluted salt solutions [19], which do not belong to the electrodialysis family, literatures on reverse electrodialysis were all removed. The remaining 3038 literatures were further analyzed.

Contributions of different institutes and countries were estimated by the affiliation of at least one author of the articles. Articles originating from England, Scotland, Wales and Northern Ireland were reclassified as from the UK, and publications from Hong Kong were combined with those from mainland China. Collaboration pattern was determined by the addresses of the authors. The term “single country/institute” was assigned if all the authors were from the same country/institute and the term “international/inter-institutional collaboration” was assigned if the articles were co-authored by researchers from different countries/institutes. The bibexcel and Pajek were employed to analyze the collaboration relationship among different countries.

All articles related to the research on electrodialysis during the past 24 years (1991-2014) were assessed from the following aspects: publication outputs, document types and languages, subject categories and journals, countries and institutes. To obtain the research trend information, “word cluster analysis” which combined the words in title, author keywords, and *Keywords Plus* was applied.

Results and Discussion

A total of 3038 electrodialysis-related literatures were published duing1991-2014 in SCIE database. Article (2875), including proceeding papers, was the predominant document type, accounting for 94.6% of the total publications, followed by review (110, 3.6%), note (19, 0.63%), and meeting abstract (18, 0.59%). The others showing less significance were correction (5), letter (4), additional correction (3), editorial material (3) and book chapter review (1). Since article was the dominant document type and was also peer-reviewed within this field, the 2875 articles were used for further analysis, while all others were discarded.

Among the 2875 articles, 2795 (97.2%) were published in English. The others were published in twelve other languages, including Japanese (19), Polish (12), French (12), Spanish (9), Chinese (8), Russian (6), German (4), Rumanian (3), Portuguese (3), Korean (2), Serbo-Croatian (1), and Italian (1). It is no surprise that English is the dominant language since the SCIE is an American-based database and more journals listed in JCR were published in English.

Publication Output

The annual number of electrodialysis-related articles was shown in Fig. 1. A total of 3834 literatures were published during the period of 1920-2014 in SCIE database. As has mentioned above, researches on electrodialysis have a long history. However, no more than 10 articles were published every year before 1968, except that 13 articles were published in 1928. During 1969-1990, the publications on electrodialysis increased at a slow rate, with an average of 20 articles published annually. However, many great improvements on electrodialysis were achieved during this period: the electrodialysis reversal technology, invented in 1969, had made continuous operation without salt precipitation or deposition possible [20]; the development of sulfonated polytetra-fluorethylene based membrane-Nafion in 1970s leaded to a large scale use in chlor-alkali industry and energy storage/conversion systems [21]; the preparation of bipolar membrane by Chlanda *et al.* [5] in 1976 had brought about many novelties in electrodialysis applications. All these improvements lay the foundations for the fast increase in publications after 1991. The annual publications almost quadrupled over the past 24 years, increasing from 59 in 1991 to 236 in 2014. Due to the lack of keywords and abstracts in articles before 1991, only articles published during 1991-2014 were analyzed in this study to give an insight into the research trend of electrodialysis.

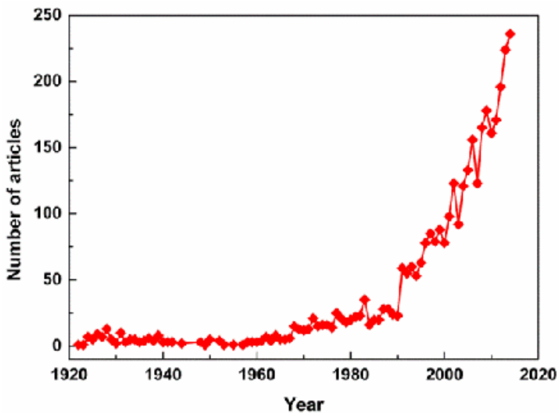

Fig. 1: Annual publication output of electrodialysis-related articles from 1920 to 2014.

Distribution of Subject Categories and Journals

According to the classification of subject categories in Journal Citation Reports (JCR), the 2875 articles were distributed in 57 subject categories. The subject categories containing over 250 electrodialysis-related articles were engineering (1682, 59%), chemistry (639, 22%), water resources (608, 21%), polymer science (473, 16%), and electrochemistry (261, 9.1%). The articles belonging to the top 5 categories covered 84.6% of the total articles published during the past 24 years. The annual publication outputs of the top 5 subject categories were shown in Fig. 2. Evidently, electrodialysis-related researches in engineering field increased rapidly during the past 24 years, while articles in other four subject categories increased with a much slower rate. This may indicate that electrolysis is a relatively mature technology, and therefore more researchers are focused on its industrial applications.

The 2875 electrodialysis-related articles were published in 466 journals in SCIE database. Among these journals, 245 (52.6%) published only one article, 69 (14.8%) published two articles. The number of journals publishing electrodialysis-related articles increased from 34 in 1991 to 95 in 2014. The top 10 most productive journals, with their IF, h-index, average number of citations per article (TC/TP), were listed in Table-1. In total, 1401 articles on electrodialysis were published in the top 10 journals, accounting for 48.7% of the total articles published during the past 24 years. Among them, *Desalination,* publishing 470 (16%) articles, was the most active journal in electrodialysis field, followed by *Journal of membrane science* (13%), and *Separation and purification technology* (4.0%). The above-mentioned three journals, comprising 33.4% of the total articles, were the core journals in electrodialysis field according to Bradford's law of scattering. *Journal of membrane science* had the highest impact factor (5.056) and h-index among the top 10 journals, and also had a high citation rate, indicating that electrodialysis-related articles published in this journal had relatively high quality and influence.

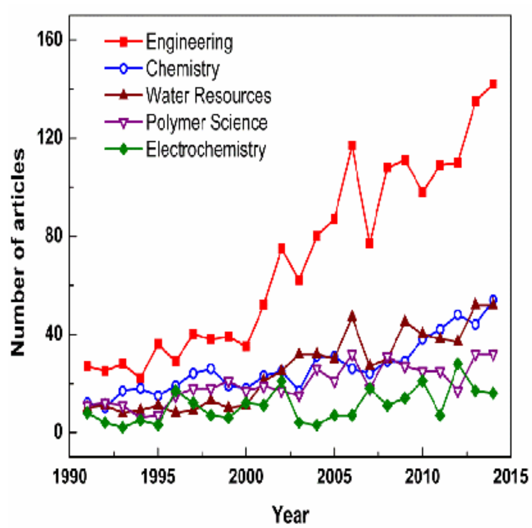

Fig. 2: Annual publication output in the top 5 subject categories.

Table-1: Top 10 most productive journals on electrodialysis research.

Journal	TP (%)	IF	H-index	TC/TP
Desalination	**470 (16)**	**3.756**	**34**	**14.6**
Journal of membrane science	**374 (13)**	**5.056**	**42**	**21.0**
Separation and purification technology	**116 (4.0)**	**3.091**	**22**	**14.5**
Russian journal of electrochemistry	**101 (3.5)**	**0.762**	**9**	**3.74**
Separation science and technology	**80 (2.8)**	**1.171**	**13**	**8.02**
Desalination and water treatment	**74 (2.6)**	**1.173**	**6**	**2.34**
Journal of colloid and interface science	**51 (1.8)**	**3.368**	**20**	**21.4**
Journal of hazardous materials	**47 (1.6)**	**4.529**	**17**	**18.4**
Journal of chemical technology and biotechnology	**44 (1.5)**	**2.349**	**13**	**14.7**
Industrial & engineering chemistry research	**44 (1.5)**	**2.587**	**14**	**9.43**

TP: total number of publications; %: the percentage of articles in total publications; IF: impact factor, based on JCR 2014; TC: total number of citations.

Performance of Authors, Institutions, and Countries

The corresponding author supervises the planning and execution of the experiment and the writing of the paper, and is usually the most experienced expert in one research group. Therefore, evaluation the performance of corresponding authors can give us information of the contribution of different research groups in a specific field. Table-2 listed the top 20 most productive corresponding authors in electrodialysis research. Bazinet from University Laval in Canada published the most corresponding-authored articles (68) and was also the highest in total outputs (87). Moon from Gwangju Institute of Science and Technology in South Korea had the highest average citations per article (31.6), and Pourcelly from Université Montpellier 2 in France had the highest h-index (22).

The author collaborations from institutional and international aspects were evaluated in this paper. A total of 1536 institutes participated in electrodialysis research, among which 984 institutes published only one article and 229 published two articles. 1812 (63.4%) of the 2859 articles were single-institute articles. Table-3 listed the top 20 most productive institutes during 1991-2014. Since electrodialysis technology has developed rapidly over the past decade, the outputs during the recent 10 years (2005-2014) were also listed in Table-3. Kuban State University from Russia ranked first in total publications and second in single-institute publications, with a total of 111 articles, followed by University Laval from Canada (85) and Technical University of Denmark (84). The proportion of collaborated articles to total publications varied from 4.41% to 97.0%, indicating significant difference in collaboration patterns of these institutes. For example, University of Science & Technology of China published the most single-institute articles (65), while only 3 collaborative articles were published by this institute. Universidade Nova de Lisboa from Portugal, however, published only one single-institute article and 32 collaborative articles. The average citation rate of single-institute articles of the 20 most productive institutes was 15.8, close to that of collaborative articles (15.4). During the past 24 years, electrodialysis technology has developed rapidly, and institutes participated in electrodialysis research also changed significantly. Some institutes only began involving in electrodialysis research during the past decades, such as Chinese Academy of Science from China, Katholieke Universiteit Leuven from Belgium, and Universidad Tecnica Federico Santa Maria from Chile, with only one or two articles published before 2005. Some institutes had reduced its interest in electrodialysis research, such as CNRS from France and Yamaguchi University from Japan, with much less articles published during the recent 10 years than before.

The 2859 articles with author address information were published by 84 countries/territories. Among the 2859 articles, 2400 (83.9%) were single country publications and the others (459, 16.1%) were internationally-collaborative publications. The top 20 countries/territories ranked by the total publications were listed in Table-4. China and France were the two largest contributors to electrodialysis research, publishing 296 and 280 articles, respectively. However, their collaboration patterns were different. 271 (91.6%) of the 296 articles from China were single-country publications, and all the other 25 collaborated articles were corresponding-authored by Chinese researchers. On the contrary, 144 articles from France were collaborated articles, accounting for 51.4% of the total publications from France and also 31.4% of the world internationally-collaborated articles on electrodialysis. The predominance of France in collaboration could also been visually confirmed by the international collaboration network of the 30 most productive countries/territories (Fig. 3). The collaboration network could be divided into three sections denoted by different colors in Fig. 3. One was centered by France with strong collaboration with Russia (34), Algeria (29), Canada (24), and Morocco (15). Another section consisted of Denmark, Portugal and Chile, with 31 collaborative-articles published involving both Denmark and Portugal. The last section consisted of the USA, Japan, South Korea, and China. The USA ranked second in the number of international-collaborative publications (62) and was the cooperative partner of 28 countries/territories. However, no strong collaboration relationship was found between the USA and other countries, because the number of collaborative-articles involving the USA and any other country was no more than 10.

The average citation rate of single-country article among the top 20 most productive countries was 14.3, and was lower than that of international-collaborative articles (18.6), indicating that international collaboration improved the impact of the articles. This phenomenon was quite remarkable in articles from Russia, Poland, and the UK, with the average citation rate of 4.3, 6.5 and 11.7 for single-country articles and 17.3, 24.4, and 26.4 for collaborative articles, respectively. For countries like Japan, the USA, Denmark, Iran, Turkey, and Belgium, however, the citation rate of single-country articles was higher than that of international-collaborative articles.

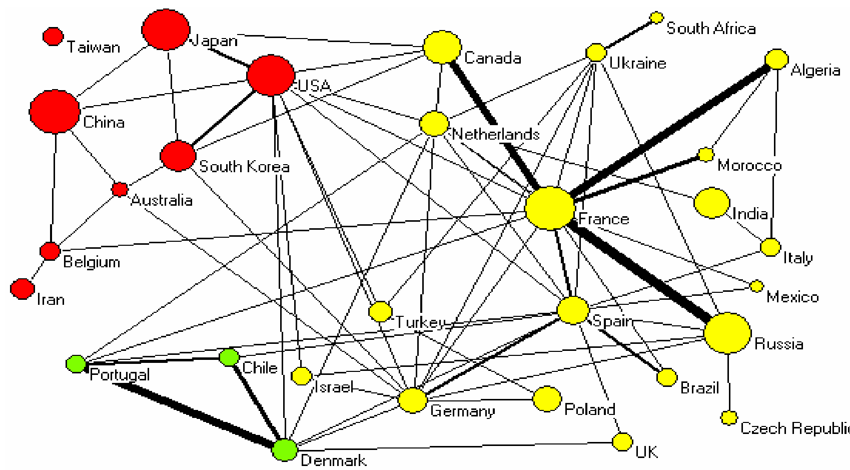

Fig. 3: International collaboration network of 30 most productive countries/territories in electrodialysis research. The thickness of the links represented the strength of collaboration, and the size of the nodes represented the number of total publications of each country. Collaboration of only one article was removed to simplify the network.

Table-2: Top 20 most productive corresponding authors in electrodialysis research.

Author	Affiliation	RP	TP	TC/TP	H-index
Bazinet, L	Univ Laval, Canada	68	87	12.0	19
Xu, TW	Univ Sci & Technol China, China	64	66	15.9	18
Moon, SH	Gwangju Inst Sci & Technol, South Korea	40	52	31.6	20
Shahi, VK	Cent Salt & Marine Chem Res Inst, India	35	39	20.8	17
Tanaka, Y	IEM Res, Japan	30	30	16.2	14
Sata, T	Yamaguchi Univ, Japan	29	33	18.3	16
Turek, M	Silesian Tech Univ, Poland	25	31	8.97	12
Shaposhnik, VA	Voronezh State Univ, Russia	21	45	7.47	10
Mohammadi, T	Iran Univ Sci & Technol, Iran	19	19	27.5	13
Ottosen, LM	Tech Univ Denmark, Denmark	18	69	15.5	18
Pourcelly, G	Univ Montpellier 2, France	18	81	22.2	22
Yoshikawa, M	Kyoto Inst Technol, Japan	17	22	27.4	16
Nikonenko, VV	Kuban State Univ, Russia	17	38	11.9	11
Elmidaoui, A	Univ Ibn Tofail, Morocco	17	31	25.1	15
Cifuentes, L	Univ Chile, Chile	17	23	7.09	8
Kabay, N	Ege Univ, Turkey	16	22	23.2	12
Sadyrbaeva, TZ	Riga Tech Univ, Latvia	14	14	3.21	4
Lamarche, F	Agr & Agri Food Canada, Canada	14	29	17.0	15
Zabolotskii, VI	Kuban State Univ, Russia	13	34	3.53	7
Perez-Herranz, V	Univ Politecn Valencia, Spain	13	17	4.94	6

RP: number of publications as a reprint author; TP: total number of publications; TC: total citations.

Table-3: Top 20 most productive institutes in electrodialysis research.

Institute	TP		Single-institute			Inter-institutional collaboration			
	91-14	05-14	R (SP 91-14)	TC/SP	R (SP 05-14)	R (CP)	TC/CP	RP (%)	R (CP 05-14)
Kuban State Univ, Russia	111	75	2 (62)	6.05	2 (38)	4 (49)	15.8	44.1	4 (37)
Univ Laval, Canada	85	73	8 (27)	10.8	3 (27)	2 (58)	11.1	68.2	1 (46)
Tech Univ Denmark, Denmark	84	60	6 (31)	19.6	6 (20)	3 (53)	12.2	63.1	3 (40)
Univ Montpellier 2, France	76	49	23 (14)	11.4	65 (3)	1 (62)	18	81.6	1 (46)
Univ Sci & Technol China, China	68	55	1 (65)	15.1	1 (53)	123 (3)	26.7	4.41	153 (2)
Voronezh State Univ, Russia	66	24	3 (46)	5.8	13 (13)	7 (20)	6.05	30.3	14 (11)
Cent Salt & Marine Chem Res Inst, India	47	20	4 (42)	19.9	7 (18)	66 (5)	19.6	10.6	135 (2)
CNRS, France	41	10	23 (14)	28.8	150 (1)	6 (27)	26.7	65.9	18 (9)
Yamaguchi Univ, Japan	39	9	5 (33)	16.8	28 (7)	54 (6)	14.7	15.4	135 (2)
Silesian Tech Univ, Poland	38	30	6 (31)	8.61	5 (23)	47 (7)	6.86	18.4	27 (7)
Ben Gurion Univ Negev, Israel	38	19	10 (26)	29.9	13 (13)	17 (12)	15.6	31.6	33 (6)
Russian Acad Sci, Russia	34	13	13 (19)	1.42	28 (7)	12 (15)	7.07	44.1	33 (6)
Univ Nova Lisboa, Portugal	33	24	244 (1)	25	150 (1)	5 (32)	13.4	97	5 (23)
Chinese Acad Sci, China	33	32	8 (27)	12.9	4 (26)	54 (6)	14.3	18.2	33 (6)
Univ Twente, Netherlands	30	17	14 (18)	29.6	22 (9)	17 (12)	41.7	40	22 (8)
Natl Acad Sci Ukraine, Ukraine	28	17	17 (17)	10.2	18 (10)	20 (11)	7.55	39.3	27 (7)
IEM Res, Japan	27	16	11 (24)	15.8	9 (14)	123 (3)	16.3	11.1	135 (2)
Katholieke Univ Leuven, Belgium	26	24	51 (6)	24.8	37 (6)	7 (20)	10.3	76.9	6 (18)
Agr & Agri Food Canada, Canada	25	10	29 (12)	18.4	37 (6)	16 (13)	13.8	52	53 (4)
Univ Tecn Federico Santa Maria, Chile	24	22	38 (8)	5.38	24 (8)	10 (16)	9.63	66.7	11 (14)

TP: total number of publications; R: Rank. SP: the number of single-institute publications; TC: total citations; CP: the number of inter-institutional collaborative publications; CP (%): percentage of collaborated publications in total publications of one institute).

Table-4: Top 20 most productive countries/territories in electrodialysis research.

Country	TP		Single-country			International collaboration			
	91-14	05-14	R (SP 91-14)	TC/SP	R (SP 05-14)	R (CP 91-14)	TC/CP	RP (%)	R (CP 05-14)
China	296	263	1 (271)	10.8	1 (239)	13 (25)	12.2	25 (100)	9 (24)
France	280	136	6 (136)	16.2	11 (47)	1 (144)	16.8	51 (35.4)	1 (89)
Japan	268	96	2 (232)	13.8	7 (73)	9 (36)	11.8	20 (55.6)	10 (23)
Russia	246	123	3 (192)	4.3	4 (85)	3 (54)	17.3	26 (48.1)	4 (38)
USA	245	152	4 (183)	19.4	2 (104)	2 (62)	15.8	24 (38.7)	2 (48)
Canada	161	112	7 (121)	15.8	5 (81)	7 (40)	21.6	32 (80.0)	6 (31)
India	154	107	5 (143)	14.9	3 (101)	21 (11)	23.9	8 (72.7)	25 (6)
South Korea	144	104	8 (114)	17.6	6 (79)	12 (30)	27.1	12 (40.0)	8 (25)
Spain	129	83	10 (78)	10.7	10 (51)	5 (51)	15.5	24 (47.1)	5 (32)
Germany	102	38	13 (55)	22.4	22 (16)	6 (47)	30.2	10 (21.3)	11 (22)
Poland	101	75	9 (93)	6.5	8 (69)	25 (8)	24.4	4 (50.0)	25 (6)
Netherlands	98	51	11 (66)	23	13 (31)	11 (32)	23.5	20 (62.5)	12 (20)
Denmark	89	64	16 (36)	19.1	15 (23)	4 (53)	12.7	21 (39.6)	3 (41)
Iran	71	66	12 (63)	12.3	9 (59)	25 (8)	8.5	7 (87.5)	23 (7)
Algeria	58	25	25 (24)	12. 7	26 (12)	10 (34)	18.1	20 (58.8)	17 (13)
Turkey	57	48	14 (49)	16.5	12 (40)	25 (8)	15.4	6 (75.0)	20 (8)
Ukraine	55	29	21 (30)	11.9	22 (16)	13 (25)	18	14 (56.0)	17 (13)
Chile	51	43	19 (34)	6.2	14 (28)	17 (17)	9.1	8 (47.1)	15 (15)
UK	51	24	17 (35)	11.7	26 (12)	18 (16)	36.4	9 (56.3)	19 (12)
Belgium	49	38	23 (28)	18.1	17 (20)	15 (21)	13.2	7 (33.3)	13 (18)

TP: total number of publications; R: Rank. SP: the number of single-country publications; TC: total citations; CP: the number of international-collaborative publications; RP (%): reprint author publications (percentage of reprint-author publications in collaborative publications).

Table-5: Top 30 most frequently used author keywords in electrodialysis research.

Author keyword	TP	R	1991-1998 R (TP)	1999-2006 R (TP)	2007-2014 R (TP)
Electrodialysis	1013	1	1 (153)	1 (357)	1 (503)
Ion-exchange membrane	327	2	2 (43)	2 (110)	2 (174)
Bipolar membrane	146	3	3 (27)	3 (54)	4 (65)
Desalination	141	4	7 (11)	4 (49)	3 (81)
Membrane	119	5	4 (24)	5 (45)	7 (50)
Anion-exchange membrane	119	5	5 (19)	6 (37)	5 (63)
Cation-exchange membrane	90	7	9 (9)	8 (30)	6 (51)
Reverse osmosis	82	8	7 (11)	10 (24)	8 (47)
Lactic acid	69	9	16 (6)	7 (33)	12 (30)
Heavy metals	62	10	25 (4)	11 (23)	10 (35)
Ion exchange	61	11	16 (6)	12 (22)	11 (33)
Concentration polarization	59	12	6 (12)	16 (17)	12 (30)
Fouling	56	13	25 (4)	9 (26)	17 (26)
Electrodeionization	55	14	42 (3)	25 (12)	9 (40)
Separation	54	15	9 (9)	14 (20)	18 (25)
Limiting current density	51	16	16 (6)	15 (18)	16 (27)
Nanofiltration	49	17	25 (4)	18 (15)	12 (30)
Copper	44	18	66 (2)	13 (21)	24 (21)
Water dissociation	42	19	66 (2)	18 (15)	18 (25)
Transport number	39	20	12 (7)	17 (16)	33 (16)
Electro-electrodialysis	38	21	66 (2)	18 (15)	24 (21)
Current efficiency	38	21	12 (7)	30 (10)	24 (21)
Modeling	36	23	25 (4)	30 (10)	22 (22)
Permselectivity	35	24	25 (4)	18 (15)	33 (16)
Wastewater	34	25	66 (2)	41 (8)	20 (24)
Amino acid	34	25	9 (9)	41 (8)	30 (17)
Fermentation	33	27	66 (2)	30 (10)	24 (21)
Bipolar membrane electrodialysis	33	27	151 (1)	205 (2)	12 (30)
Mathematical modeling	31	29	151 (1)	46 (7)	21 (23)
Demineralization	31	29	12 (7)	22 (13)	47 (11)

TP: total number of publications; R: Rank of total articles. R (TP): Rank and number of articles published during each period.

Author Keywords Analysis

The author keywords of an article can provide the information that the authors would most likely to express to the readers, and a statistical analysis of them can offer the research hotspot information of a particular field. Among the 2875 articles, 2223 with author keywords information were analyzed in this study. When analyzing the frequency of the author keywords used during the past 24 years, the synonymic single words and congeneric phrases were summed. For example, "ion-exchange membrane", "ion-exchange membranes", "ion-exchange membrane (IEM)", and "ion exchange membrane" were all counted as "ion-exchange membrane". The top 30 most frequently used author keywords were listed in Table-5. Except the search word "electrodialysis" itself, membrane-related author keywords, including "ion-exchange membrane", "bipolar membrane", "membrane", "anion-exchange membrane", and "cation-exchange membrane", all ranked top 10 during 1991-2014 and each eight-year intervals. This suggested the great significance of IEM in electrodialysis processes. The keyword "desalination" ranked 4 in total publications, indicating that desalination was one of the most important applications of electrodialysis. Other application-related keywords, such as "lactic acid", "heavy metals", "copper", "wastewater", "amino acid", and "demineralization", were also included in the top 30 most frequently used author keywords. The electrodialysis processes such as "electrodeionization", "electro-electrodialysis", and "bipolar membrane electrodialysis" were three more frequently studied techniques. For treatment of practical wastewater or fermentation broth which was more complicated than pure solution, process integration was often required. As shown in Table-5, "reverse osmosis" and "nanofiltration" were the two most frequently studied integration processes with electrodialysis.

Hot Topics

Based on the author keywords analysis, the research hotspots on electrodialysis could be classified into three aspects: IEM-related research, applications of electrodialysis, and process integration of electrodialysis. IEMs are the most important components of the electrodialysis stacks and their properties, including selectivity, electrical resistance, chemical, mechanical and thermal stability, will determine the performance of an electrodialysis stack. The preparation, application, and development of IEMs had been reviewed in detail in literature [10, 14, 22]. Therefore, we only focused on the applications and process integration of electrodialysis in this paper. In order to analyze the historical development of them, a new method called "word cluster analysis" was applied in this study. This method has already been used to study the research trend on drinking water [23], nitrate removal [24], and atmospheric simulation [25]. The procedure of this method was described in detail in literature [23].

Applications of Electrodialysis

Electrodialysis is a mass transfer process capable of separating ionic species from aqueous solutions and molecular components, and has been used today in various applications from water desalination, wastewater treatment to organic acids production. Table-6 illustrates the operation conditions and performances for some electrodialysis applications. Desalination was the dominant application of electrodialysis (Fig. 4), and has gained increased attention in recent years due to the serious shortage of world water resources. Desalination by electrodialysis was put into industrial applications during 1960s, which was about 10 years earlier than desalination by reverse osmosis (RO). Today, a lot of electrodialysis installations can be found in many countries, such as the USA, Japan, Russia, and China. Most of the large-scale electrodialysis installations are used for production of potable water from brackish water (salt content about 1-8 g/L), due to its economic advantage and higher water reclamation rate over other processes such as RO and multistage flash evaporation. However, when desalting water with high salt content like seawater, RO is usually a more economic choice for large-scale production and electrodialysis is more desirable in domestic systems such as cottages, offices, and yachts [26]. A recent study indicated that electrodialysis had the potential to desalting water produced from fossil-fuel wells which was three to six times saltier than seawater. However, the purpose of this process is to enable its reuse to be injected into subsequent wells, rather than produce potable water [27].

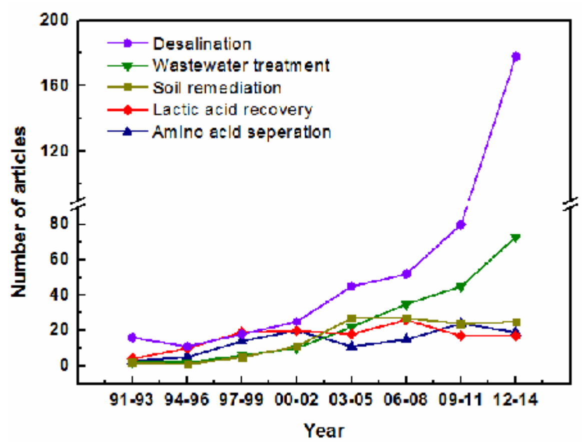

Fig. 4: Research trends of different applications of electrodialysis.

Electrodialysis has been widely used in industrial and agricultural wastewater treatment, and its application scope is expanding gradually. Electrodialysis had been extensively used for removal or recovery of hazardous/useful metals from wastewater. The main hazardous ions that can be treated by electrodialysis and their sources were listed in Table-7. Electroplating and metallurgical industry wastewaters usually contained heavy metals that can be effectively recovered by electrodialysis, including nickel [28, 29], copper [30], chromium [31, 32], zinc [33], and Cadmium [34]. Recovery of lead from battery industry wastewater can also be efficiently achieved by electrodialysis [35]. Acid and base can be produced from wastewater by EDBM and reused in the production process [36-38]. Fukumoto and Haga [39] reported that electrodialysis could remove approximately 99% of the excess nitrogen and phosphorus in swine wastewater and decrease 58% of the color density. Kang *et al*. [40] proved that electrodialysis was a cost-effective way to pretreat the butyl-acrylate wastewater and recover the organic salts. In general, electrodialysis is considered as a simple but effective method for wastewater treatment. However, there are still some limitations: only ionic components can be removed by electrodialysis, uncharged pollutants cannot be removed; when the salt concentration is too high, or high purity of the product water is required, electrodialysis is not economically competitive with other wastewater treatment techniques.

Besides removing metals from aqueous solutions, heavy metals from polluted solid matrices can also be removed by electrodialytic remediation, a technology based on the combination of the principles of electrokinetic movement of ions and electrodialysis [41]. Electrodialytic remediation was developed at the Technical University of Denmark in early 1990s, and has thereafter been utilized for removal of heavy metals from contaminated soils [42, 43], fly ash [44, 45], mine tailings [46, 47], harbor sediments [48, 49], CCA treated timber waste [50] (Table-7). As shown in Fig. 4, the number of publications on electrodialytic soil remediation increased slowly before 2003, and kept relatively stable thereafter. As a newly developed *in-situ* remediation technique, electrodialytic process had proved to be competitive in cost and effectiveness to other methods in use. However, there were still some disadvantages: (I) the solubility of the pollutants and pollutants desorption from the solid matrix can significantly affect the remediation efficiency. Heavy metals in metallic states were difficult to dissolve and separate from the matrix. (II) The process was also not efficient when the target ion concentration was low and non-target ion concentration was high. (III) Acidic conditions and anode corrosion may cause problems in *in-situ* performance.

Table-6: Operation conditions and performances of some electrodialysis application cases.

Application	Operation conditions	Operation performances	Reference
HCl and NaOH recovery from softened RO brines	Three compartment EDBM; membrane area 200 cm^2, current density 250-1000 A/m^2	Acid concentration 0.8 M; base concentration 1.0 M; current efficiency 60-80%	[62]
Regeneration of inorganic acid and base from a metal washing step wastewater	Three compartment EDBM; membrane area 64 cm^2; current density 60 mA/cm^2	Current efficiency 69% for acid and 80% for base; energy consumption 5.5 kW h/kg acid and 4.8 kW h/kg base	[37]
Removal and recovery of Ni^{2+} from electroplating rinse water	Electrodeionization reversal; membrane area 158.4 cm^2; initial Ni2+ concentration 50 mg/l	Removal efficiency 97%; concentrating factor 79.2; current efficiency 32.6%; energy consumption 1.02 $kW·h/m^3$	[28]
Concentration and purification of chromate from electroplating wastewater	Two-stage electrodialysis system; the first stage to concentrate $HCrO_4^-$ and the second stage to separate the monovalent ion from $CrO4_2^-$; initial Cr(VI) concentration 418 mg/l	Cr(VI) was concentrated up to 191% in the first stage, and 45% of chloride was separated at the second stage	[32]
Remidiation of soil contaminated by copper	Electrodialysis with one soil compartment placed between two electrode compartments; current density 0.1 and 0.2 mA/cm^2 soil	The copper concentration reduced from 1360 to below 40 mg Cu/kg dry soil	[41]
Production of lactic acid	Two compartment EDBM; current density 75 mA/cm^2; Initial feed lactate concentration 100-150 g/l	Current efficiency 80.8-83.7%; energy consumption 0.54-0.71 kWh/kg lactate	[53]
Production of citric acid	Two compartment EDBM, membrane area 20 cm^2; current density 1000 A/m^2	Current efficiency 70%; citric acid concentration 30 g/l	[54]
Separation of gluconate	Two compartment conventional electrodialysis; membrane area 200 cm^2	Current efficiency 79-88%; energy consumption 0.83 kWh/kg gluconate	[55]
Concentration of lysine	Conventional electrodialysis; membrane area 7.07 cm^2; current density 75 mA/cm^2	Current efficiency 74,1%; energy consumption 4.6 kWh/kg lysine	[57]

Table-7: Sources of hazardous ions and the number of publications on their treatment by electrodialysis.

Ions	Source		TP
	Aqueous phase	Solid phase	
Copper (Cu)	Electroplating wastewater; copper smelting wastewater	Contaminated soils; fly ash; contaminated harbor sediments; CCA treated timber waste; copper mine tailings	182
Chromium (Cr)	Electroplating wastewater; chromium etching solutions; textile wastewater	Contaminated soils; CCA treated timber waste	95
Nickel (Ni)	Electroplating wastewater; spent electro-less nickel plating bath; spent NiMH batteries leachate	Contaminated soils	91
Fluorine (F)	fluoride-rich brackish water; drinking water; groundwater;	/	76
Zinc (Zn)	Zinc-Coating wastewater; zinc smelting wastewater; electroplating wastewater	contaminated soils	61
Lead (Pb)	Battery manufacturing wastewater;	Contaminated soils; contaminated harbor sediments; fly ash	54
Cadmium (Cd)	Electroplating wastewater	Fly ash; wastewater sludge; contaminated soils; contaminated harbor sediments	50
Boron (B)	Industrial landfill leachate; RO permeate; seawater; groundwater	/	50
Arsenic (As)	Copper smelting wastewater; acidic electrolytes; drinking water;	CCA treated timber waste; fly ash; contaminated soils	28
Cobalt (Co)	Spent NiMH battery leachate; waste lithium-ion battery leachate	/	22
Lithium (Li)	Superfine aluminum hydroxide production wastewater; seawater; lake brines; waste lithium-ion battery leachate	/	15

TP: total number of publications; CCA: chromated copper arsenate.

Electrodialysis is considered to be the most competitive technology to recover or produce organic acids due to its predominance in simultaneous supply of H^+ and OH^- without salt introduction or discharge [51]. For example, utilization of electrodialysis can significantly simplify the lactic acid recovery process and elevate the lactic acid production by reducing the product inhibition [52, 53]. Electrodialysis has also been used for production of citric, amino, and gluconic acid and concentration of propionate and lysine [54-57], etc.

Process Integration of Electrodialysis

Practical wastewater or feeds from fermentation are usually complicated. Therefore, supplementary processes are needed to satisfy the discharge standard or realize high-quality production. Xu and Huang [58] have elaborated integration of electrodialysis with other separation processes. As described by Xu and Huang, the integrated processes can mainly be classified into three groups: integration of electrodialysis with chemical units operations, pressure-driven membrane processes and biochemical unit operations. As shown in Fig. 5, the most frequently studied integration processes was pressure-driven membrane process, such as RO, nanofiltration (NF), and ultrafiltration (UF). All these integration processes showed an increased trend along with the increase of electrodialysis research, and researches on electrodialysis combined with RO increased significantly during the past 3 years. RO can be coupled with electrodialysis in many ways and for various purposes. When producing potable water from brackish water or seawater, RO processes often suffered from low recovery of product water, while electrodialysis alone cannot achieve complete removal of salts and uncharged components. Therefore, researchers used electrodialysis as a pretreatment process of RO to remove the salts to obtain higher recovery of product water without compromising its quality [59, 60]. The combined electrodialysis/RO can also be applied to concentrate some valuable solutions. For example, in food industry, an industrial mussel cooking juice was first desalinated by electrodialysis and then concentrated by RO to produce a natural aroma concentrate [61]. Mondor *et al* [62] produced concentrated nitrogen fertilizer from liquid swine manure by pre-concentrating the nitrogen by electrodialysis and further concentrating by RO. For extraction and purification of dissolved organic matter from seawater or fresh waters for research purpose, electrodialysis was used to desalinate the concentrated solution of RO [63, 64]. Using EDBM to desalinate and produce mixed acid and base simultaneously from RO concentrate may be economically viable for inland RO facilities when the options for concentrate disposal were limited [65-67].

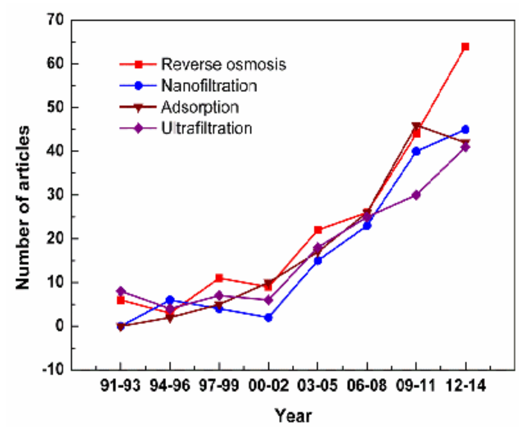

Fig. 5: Research trends of different combination technologies of electrodialysis.

Nanofiltration is an effective method to remove the natural organic matter and various micro-pollutants in surface water [68, 69]. However, the water recovery higher than 80% is economically undesirable due to the scaling problem and increased costs. Reports proved that desalinating the NF retentate by electrodialysis can solve the scaling problem and thus enhance the potable water production [70]. NF can be used as a pretreatment process to remove the impurities and undertake partial desalination before electrodialysis for water recovery from pulp bleaching effluents [71, 72] and organic acid recovery from fermentation broth [73, 74].

Ultrafiltration was usually used as a pretreatment process to recover bacterial cells from fermentation broth and ensure stable and reliable operation of electrodialysis [75, 76]. In addition, a newly developed membrane technology, electrodialysis with UF membrane (EDUF), with UF membrane stacking in the electrodialysis device, is capable of separating charged valuable organic components from complex feedstock. EDUF was first introduced by Bazinet *et al.* to isolate polyphenols from tobacco extract [77] and from green tea infusion [78]. In recent years, this technology has been studied to separate chitosan oligomers [79], bioactive peptides [80, 81], and anthocyanins [82] from complex matrices.

Adsorption can not only be used as the pretreatment process of electrodialysis to remove any pollutant that might foul the IEMs [83], but also the post treatment process to further remove any unwanted chemicals [84, 85]. In general, the stand-alone electrodialysis may not be able to remove the pollutants to a desired level or produce water or other product with high quality, integration with other processes is necessary in industrial applications. Therefore, it can be predicted that researches on combination of electrodialysis with other processes will be more prevailing in the future.

Despite its long-term development, electrodialysis technology still has some problems to be solved to become economically competitive with other processes: the high cost of IEMs and their scaling and fouling problems and the concentration polarization phenomenon which decreases the efficiency and increases the energy consumption. To solve these problems, researchers have proposed some new techniques. One is the application of intensive current regimes when the applied current exceeds its "limiting" value. This mode allows reduction of the membrane area, resulting in lower investment costs of electrodialysis plants [86]. The state-of-the-art and perspectives of overlimiting current mode in electrodialysis has been described in detail in literature [86, 87]. Another is the use of pulsed electric field (PEF) instead of conventional direct current [87]. PEF can prevent concentration polarization phenomenon and improve mass transfer. But most importantly it can mitigate the scaling and fouling on membrane surface. Successful application of PEF in electrodialysis has been reported to decrease membrane scaling [88-90] and fouling [91-93]. Mikhaylin *et al*. [94] applied the PEF to EDBM for the first time, and demonstrated that PEF inhibited scale formation and OH^- leakage, resulting in accelerated EDBM process and increased membrane lifetime. The overlimiting current mode and PEF mode are probably the two most important new directions in electrodialysis development.

Conclusions

By analyzing the 2875 electrodialysis-related articles from the SCIE database, this bibliometric study provides an overview of research in electrodialysis technology and identify some research hotspots during 1991-2014. Electrodialysis-related publications had increased significantly during the past 24 years. Articles were published in 466 journals in 57 subject categories. The journal *Desalination* published the most articles in this field, followed by *Journal of membrane science* and *Separation and purification technology.* China and France were the two biggest contributor to electrodialysis publications, but their collaboration patterns were different. The keyword analysis revealed that the research on electrodialysis can be separated into three aspects: IEM-related research, applications of electrodialysis, and process integration of electrodialysis. Researches on these three aspects are predicted to increase in the future.

Acknowledgment

The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China (Grant No. 51278050).

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