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Research trends on nitrate removal: a bibliometric analysis

Wenli Huang[a,b], Baogang Zhang[a,*], Chuanping Feng[a], Miao Li[c], Jing Zhang[a]

[a]*Beijing Key Laboratory of Water Resources & Environmental Engineering, School of Water Resources and Environment, China University of Geosciences (Beijing), Beijing 100083, China*
Tel. +86 10 8232 2281; Fax: +86 10 8232 1081; email: zbgcugb@gmail.com
[b]*Doctoral Program in Life and Environmental Sciences, University of Tsukuba, Tsukuba 3058572, Japan*
[c]*School of Environment, Tsinghua University, Beijing 100084, China*

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ABSTRACT

Nitrate contamination has become an increasing problem globally and has aroused the interests of researchers. The present research was designed to evaluate the global scientific outputs in the Institute of Scientific Information subject category of "nitrate removal" for the past 20 years, based on the online version of the Science Citation Index Expanded, Web of Science, from 1991 to 2010. Articles related to nitrate removal were assessed from the aspect of distributions of source countries, institutes, the distributions of words in the title, author keywords, and KeyWords Plus. The new method named "word cluster analysis" was also employed to further investigate the research status on nitrate removal. Three categories including removal field, removal methods, and product were also introduced to analyze the research trends in nitrate removal. The results showed that researchers paid most attention to "soil" and "water" in the removal field. "Denitrification" possessed the largest percentage among the removal methods, indicating that biological means were dominated for nitrate removal. Moreover, "nitrogen" as the ideal product of nitrate removal was the most predominant among the product, which was the goal of the technique for nitrate removal. The impacts of the most cited articles each year were also discussed with the article life information.

Keywords: Scientometrics; Research trend; Nitrate removal; Denitrification

1. Introduction

Nitrate contamination has become an increasing problem globally due to the extensive use of nitrogen fertilizers and improper treatment of wastewater from industrial sites [1–3]. The over fertilization and sewage can lead to excessive nitrate levels in crop and groundwater [4]. With the human consumption of high levels of nitrate food or drinking water, it is possible that nitrate will be converted into nitrites or nitrosamines in the stomach, which may cause methemoglobinemia (acute "blue baby" syndrome) in infants and gastrointestinal cancer in adults [5–6]. The United States, Canada, the European Economic Community (EEC), and the World Health Organization (WHO) have set standards to regulate the nitrate concentration in drinking water in order to protect consumers from the side effects with the high nitrate intake [7–10]. A maximum limit of 50 mg/L NO_3^- in drinking water was recommended by EEC [10] and the WHO [7].

Several methods have been employed to reduce nitrate due to its health risk [11–13]. Physical methods, like reverse osmosis, ion exchange, and electrolysis, have been demonstrated effectively for nitrate

*Corresponding author.

removal and have been applied in many factories and waterworks [14–16]. Chemical methods can use metal or hydrogen to reduce nitrate to nitrogen theoretically. However, nitrite and ammonia are the usual main products, not nitrogen [17]. Biological methods including autotrophic denitrification and heterotrophic denitrification can remove nitrate with nitrate-reducing bacteria [18]. Scientific articles on nitrate removal have demonstrated a rapid increase in quantity over the past several decades. Shrimali et al. described a comprehensive account of the methods/techniques developed and used during the last 10 years for nitrate removal in 2001 [19]. A number of papers presenting the latest research achievements have been published in authoritative scientific journals such as *Nature* and *Science* [20,21]. The bibliometric method has been widely applied to the analysis of scientific production and research trends in kinds of topics, for example, global biodiversity [22], adsorption technology [23], climate change [24], water resource [25], wetland [26], solid waste [27], and desalination [28]. The Science Citations Index Expanded (SCI-EXPANDED), from the Institute of Scientific Information (ISI) Web of Science databases, is the most important and frequently used source for a broad review of scientific accomplishment in all fields. Whereas conventional bibliometric methods center on citation and content analysis, the newly-developed bibliometric analysis evaluates the scholarly outputs of authors, institutions, countries, and more information, closer to the research itself, such as words in the title [29], author keywords and KeyWords Plus [30] should be introduced in the study of research trends.

In this research, a bibliometric analysis of language, source country, institution and the most cited papers is performed to describe research status from the aspect of nitrate removal. In addition, the distributions of words in the title, author keywords, and Key Words Plus are also analyzed to study the research trends during the period 1991–2010. These investigations are helpful for researchers to realize the research advancements and clarify the future research direction for nitrate removal.

2. Data sources and methodology

Documents used in this study were based on the online database of the SCI, retrieved from the ISI Web of Science, Philadelphia, USA. According to *Journal Citation Reports* (JCR), it indexed 7,387 major journals with citation references across 174 scientific disciplines in 2010. Five search terms, including: "nitrate removal", "remove nitrate", "nitrate reduction", "reduce nitrate" and "denitrification" were employed as the keywords to search titles, abstracts, and keywords from 1991 to 2010. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as being one country. Articles from Hong Kong were not included in China. Besides, the reported impact factor (IF) of each journal was obtained from the 2010 JCR. Collaboration type was determined by the addresses of the authors, where the term "single country publication" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative publication" was designated to those articles that were coauthored by researchers from multiple countries. The term "single institute publication" was assigned if the researchers' addresses were from the same institute. The term "inter-institutionally collaborative publication" was assigned if authors were from different institutes.

The words in titles were separated, and then conjunctions and prepositions such as "and", "with", "of", "by", "in", and "on" were discarded, as they were meaningless for further analysis. All keywords, both those reported by authors and those assigned by ISI, as well as words in the title were identified and separated into four five-year spans (1991–1995, 1996–2000, 2001–2005, and 2006–2010, respectively), then their ranks and frequencies were calculated, and different words with identical meaning and misspelled keywords were grouped and considered as a single keyword.

3. Results and discussion

3.1. Characteristics of publication outputs

From this research, 14 document types were found among the total 36,488 publications during the 20-year study period, and the most frequent document type was articles (31,064), which were responsible for 85% of the total publications. Proceeding papers (3,759; 10%), and reviews (1,143; 3%) also comprised a significant portion of total. The others were less significant, including note (174), meeting abstracts (167), editorial material (88), letters (43), corrections (25), reprints (9), news items (8), addition corrections (5), discussion (1), bibliography (1), and book review (1). As journal articles were dominant in the document types, they were identified and further analyzed. As for the publishing language, 30,140 or 97% of the 31,064 journal articles were written in English, followed by German (214), Chinese (147), French (124), Japanese (113), Portuguese (91), Spanish (56), Russian (48), Czech (45), Polish (31), Hungarian (20), Korean (8), Italian (7), Rumanian (4), Slovak (3), Lithuanian (3), Turkish (3), Dutch (3), and Serbo-Croatian (1), which were minor publication languages in nitrate removal research.

The number of both the SCI documents and articles was analyzed and displayed respectively in Fig. 1 to see the research trend during the last 110 years. Along with the development of SCI, nitrate removal research continually grew in this long period, started to go up significantly in the year of 1975 and rocketed in the past two decades (Fig. 1). The number of articles increased more than four times i.e. 958 in 1991 to 2,862 in 2010. This rising number of publications suggested a clear research focus on nitrate removal, due to the gradually increasing understanding of the harm of nitrate.

In 2009, JCR of the ISI contained 7,387 major journals with citation references across 174 scientific disciplines in the SCI. Based on the classification of subject categories in JCR, the publication output data of nitrate removal research were distributed in 151 SCI subject categories during the last 20 years. The five most common categories were Environmental Sciences (6,069 articles; accounting for 19.5% of the total), Engineering Environmental (2,784; 9.0%), Soil Science (2,736; 8.8%), plant science (2,599; 8.4%), and Water Resources (2,417; 7.8%), respectively. Other major subject categories in nitrate removal research included: Microbiology, Biotechnology Applied Microbiology, Chemistry Physical, Engineering Chemical, Agronomy, Biochemistry Molecular Biology, Ecology, and Marine Freshwater Biology. The number of scientific articles in Environmental Sciences was larger than that in other subject categories and exhibited sustaining growth during the period covered, except in the year 2010 (Fig. 2), suggesting that the environmental impact of nitrate has been focused on. The number of scientific articles in *Engineering Environmental and Water Resources* increased first, and then decreased gradually. After that, it increased again, with a significant increasing tendency. However, the number of articles without a significant change in the soil science and continuously drop in the plant sciences, indicating that nitrate removal research had differently developing trend in these subject categories.

Articles were published in a wide range of 2,961 journals, and the top 20 most productive journals are summarized in Table 1, along with IF of each journal in 2010, number of papers that the corresponding journals published, the number of citations that each journal received for these articles, the number of cited reference, respectively. In this particular research field, *Water Research* published the most articles (690; 2.2%), while *Applied and Environmental Microbiology* ranked second with 461, *Soil Biology & Biochemistry* ranked third with 448, *Journal of Environmental Quality* ranked fourth with 431, and *Environmental Science & Technology* ranked fifth with 412 the 20 (0.6%) journals published 5,986 or 19.3% of the total 31,064 articles. The average citation rate of journals in nitrate removal is the most direct indicator for assessing the impacts of journals: the higher the citation rate is, the greater the journal's impact is on this field. In addition, the average cited reference numbers per article also show the importance of each article published in this research field.

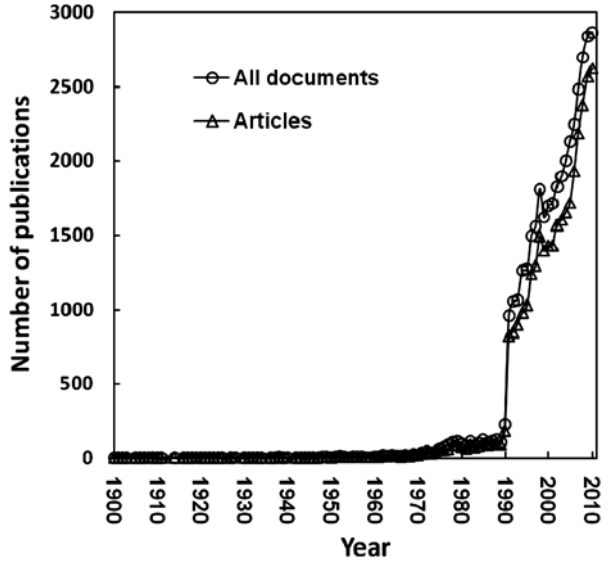

Fig. 1. World SCI-EXPANDED journal publications with nitrate removal, remove nitrate, nitrate reduction, reduce nitrate or denitrification in titles during 1900–2010.

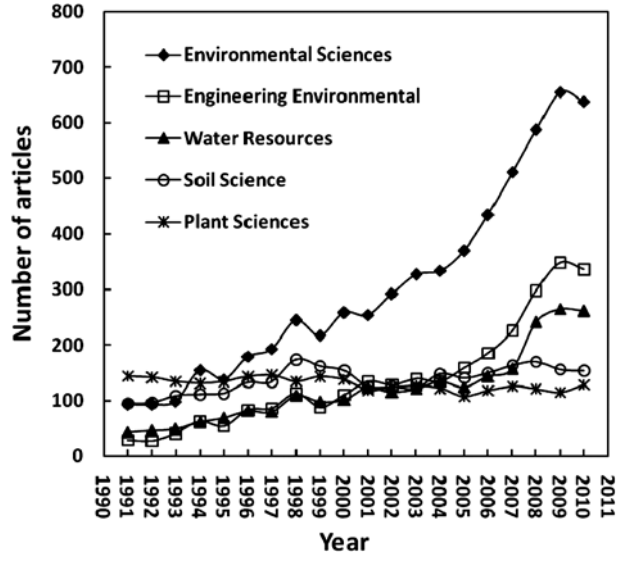

Fig. 2. Comparison of the growth trends of the top five productive subject categories.

Table 1
The top 20 most productive journals based on total number of articles

Journal	TP	TP (%)	IF	TC	TC/TP	NR	NR/TP
Water Research	690	2.2	4.546	16,190	23.46	18,502	26.81
Applied And Environmental Microbiology	461	1.5	3.778	18,696	40.56	19,551	42.41
Soil Biology & Biochemistry	448	1.4	3.242	11,864	26.48	16,800	37.50
Journal of Environmental Quality	431	1.4	2.236	10,379	24.08	16,564	38.43
Environmental Science & Technology	412	1.3	4.825	11,159	27.08	15,331	37.21
Plant and Soil	350	1.1	2.773	6,173	17.64	13,299	38.00
Bioresource Technology	301	1.0	4.365	3,317	11.02	8,023	26.65
Geophysical Research-Atmospheres	290	0.93	3.303	10,993	37.91	14,435	49.78
Soil Science Society of America Journal	265	0.85	1.866	7,611	28.72	9,475	35.75
Journal of Plant Nutrition	244	0.79	0.726	1,847	7.57	6,918	28.35
Biology and Fertility of Soils	242	0.78	2.156	4,524	18.69	7,634	31.55
International Journal of Systematic and Evolutionary Microbiology	237	0.76	1.93	7,962	33.59	14,972	63.17
Chemosphere	221	0.71	3.155	3,372	15.26	6,604	29.88
Journal of Hazardous Materials	220	0.71	3.723	1,971	8.96	6,625	30.11
Marine Ecology-Progress Series	217	0.7	2.483	6,934	31.95	10,884	50.16
Water Science and Technology	197	0.63	1.056	516	2.62	3,601	18.28
Environmental Technology	196	0.63	1.007	1,213	6.19	4,674	23.85
Applied Catalysis B-Environmental	192	0.62	4.794	5,441	28.34	6,880	35.83
Biogeochemistry	188	0.61	2.674	6,091	32.40	9,784	52.04
Water Environment Research	184	0.59	0.89	1,679	9.13	4,945	26.88

Note: TP: total number of articles, IF: 2010 ISI Impact factor, TC: total citation count, NR: cited reference count, TC/TP: average of citations in a paper, and NR/TP: the average cited reference count per article.

3.2. Distribution of country/territory articles

The contribution of different countries/territories was estimated by the location of the affiliation of at least one author of the each published paper. Of all the 28,441 articles with author addresses, 22,544 (79%) were single country articles and 5,897 (21%) were internationally collaborative articles. The 20 most productive countries/territories were summarized in Table 2, along with the number of total articles and total citations for single country articles and internationally collaborative articles, respectively. Among the top 20 productive countries/territories are 2 North American countries, 1 South American country, 11 European countries, 5 Asian countries, and Australia. The USA published the most total articles (8,318, 29%), single-country articles (6,110, 27%), internationally collaborative articles (2,208, 37%), followed by Germany (2,544, 9%), China (2,330, 8%), UK (2,086, 7%), Japan (2,080, 7%). As was consistent with other bibliometric analyses [31–33], economic developments were correlated with the academic outputs: the seven industrialized countries (G7 group: the USA, Germany, Japan, France, the UK, Canada, and Italy) and four major developing countries ("BRIC": China, India, Brazil, and Russia) were all among the top list of 20 countries. Among the top 20 most productive countries/territories, Switzerland possessed the highest percentages of internationally collaborative articles (58.94%), while the lower were Taiwan (17.42%) and India (19.02%). Another observation on the academic exchange would be that internationally collaborative articles generally drew more citations than those produced by individual countries.

A comparison of the publication trends of the top five countries which included at least 2,000 articles is shown in Fig. 3. The United States maintained a stable and fast growth, as in other research fields, such as the rapid development of stem cell research [34]. In the rural communities of America, there was no centralized water supply. The local groundwater was the major source of drinking water and was generally produced from private wells, which produced water that exceeded the maximum permissible level of NO_3–N [35]. China had the highest growth rate in the number of articles since 2001 and ranked second in 2006. The government established a series of positive policies and spent a lot of money to repair the environment since Tai lake broke out the worst algae event in 2001, which contributed to the rapid development of nitrate removal research in China [36]. The other three countries namely Germany, UK, and Japan only had a low increase in articles. This phenomenon had a

Table 2
Top 20 most productive country/territory based on total number of articles

Country	TP	Single-country				Internationally-callaborated			
		SP	SP (%)	TC	TC/SP	CP	SP (%)	TC	TC/SP
USA	8,318	6,110	73.46	153,133	25.06	2,208	26.54	56,430	25.56
Germany	2,544	1,306	51.34	28,169	21.57	1,238	48.66	30,732	24.82
China	2,330	1,633	70.09	11,808	7.23	697	29.91	7,918	11.36
UK	2,086	1,168	55.99	28,852	24.70	918	44.01	23,964	26.10
Japan	2,080	1,562	75.10	21,448	13.73	518	24.90	8,488	16.39
Canada	1,646	1,062	64.52	17,082	16.08	584	35.48	14,410	24.67
France	1,627	876	53.84	16,022	18.29	751	46.16	16,762	22.32
Spain	1,149	770	67.01	10,396	13.50	379	32.99	8,065	21.28
India	1,104	894	80.98	7,874	8.81	210	19.02	2,511	11.96
Australia	910	509	55.93	7,995	15.71	401	44.07	9,315	23.23
Netherlands	907	442	48.73	11,287	25.54	465	51.27	13,222	28.43
Italy	899	540	60.07	8,632	15.99	359	39.93	8,292	23.10
South Korea	738	497	67.34	4,879	9.82	241	32.66	2,345	9.73
Denmark	632	320	50.63	8,795	27.48	312	49.37	8,990	28.81
Sweden	598	331	55.35	6,867	20.75	267	44.65	8,624	32.30
Brazil	530	373	70.38	2,986	8.01	157	29.62	3,630	23.12
Taiwan	511	422	82.58	5,667	13.43	89	17.42	964	10.83
Russia	463	284	61.34	1,068	3.76	179	38.66	3,490	19.50
Switzerland	414	170	41.06	3,754	22.08	244	58.94	7,520	30.82
Turkey	412	324	78.64	2,840	8.77	88	21.36	1,150	13.07

Note: TP: total number of articles, SP: single country articles, CP: internationally collaborative articles, and TC: total citation count.

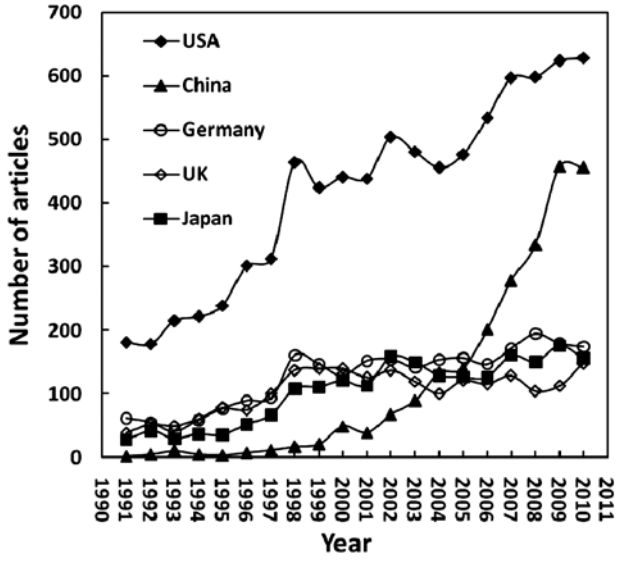

Fig. 3. Comparison of the growth trends of the top five productive countries.

relationship with all of them being developed industrial countries and non-agricultural countries with less polluting enterprise and more advancing technology.

3.3. Distribution of institute analysis

The contributions of different institutes were estimated by the affiliation of at least one author. Of all articles with author addresses, 12,585 (44%) were single institute articles and 15,856 (56%) were inter-institutionally collaborative articles, indicating that nitrate removal research called for teamwork among institutes. Among the top 20 institutes (Table 3), 10 were in the USA, 3 in Canada, 2 in China and 1 each in France, Russia, Japan, Spain and Brazil, respectively. The Chinese Academy of Sciences had the most total articles (491), independent articles (137), and inter-institutionally collaborative articles (354), followed by Agricultural Research Service, the United States Department of Agriculture (USDA ARS) (408), Institute National Research Agronomique (INRA), France (315), Russian Academy of Sciences (265), and US Geological Survey (256). The result of institutes' output should be interpreted in the context of bias. The Chinese Academy of Sciences and the Russian Academy of Sciences had over 100 branches in different cities. At present, the articles of these two institutes were pooled under one heading, while articles divided into branches would result in different rankings. It should be noted that the US Geological Survey and University of British Columbia, Canada had the highest average citation rate in single institute and cooperative institute, respectively. The higher the citation rate was, the greater the institute's posited in the field. Another observation from Table 3 would be that the percentage of collaborative articles was generally higher than that of those individual institutes, which proved that the academic communities of nitrate research were more collaborated once again.

3.4. Hot issues

The title, keywords and KeyWords Plus of an article always includes the information that the author would most likely express to the readers. In order to analyze the historical development of science more completely and precisely, and to discover new research trends more importantly, a new method named "word cluster analysis" was employed, which combined the paper titles, author keywords, and KeyWords Plus (Table 4). This method had been applied to the analysis of research trends in global climate change [24], risk assessment [37], and atmospheric simulation [29].

The 31,064 articles had 82,476 unique keywords, which appeared 669,753 times. However, 51,608 or 62.57% out of these 82,476 keywords appeared in one paper, and 73,469 (89.08%) keywords appeared in less than 10 papers. We present the more than 1,000 times frequently used keywords within each of the 5-year intervals during 1991–2010 in Table 4. During this period, 35 or 0.04% of the 82,476 keywords appeared 91,408 times and thus were responsible for 13.64% of the total keyword occurrences. The frequency of keywords and their ranks followed the power-law distribution: there was a small group of keywords that were widely-used, whereas most keywords were not employed frequently. This power-law distribution had also been discovered in other bibliometric studies [22].

Research trends in nitrate removal were separated into three categories-removal field, removal methods, and product. Referring to the removal field in nitrate removal research, "soil" and "water" had a distinctly higher rank (the fourth and sixth) over the last two decades. However, the percent use of "soil" dropped from 16.2 in 2001–2005 to 11.6 in 2006–2010, while the percent use of "water" increased year by year and surpassed "soil" in 2006–2010. This showed that more attention was paid to the research on "water" since 2006. Moreover, it was worth noting that the rank or percentage of "wastewater" from 55(2.4%) in 1991–1995 increased to 10(10.4%) 2006–2010 and the "groundwater" from 44(2.8%) increased to 20(5.8%), which demonstrated that the "wastewater" was the main research field in water research, followed by "groundwater". This is because groundwater is an

Table 3
Top 20 most productive institutes based on total number of articles

Institute	Single-institute					Inter-institutionally collaborative			
	TP	SP	SP (%)	TC	TC/SP	CP	CP (%)	TC	TC/SP
Chinese Academy of Sciences, China	491	137	27.90	1,296	9.46	354	72.10	2,945	8.32
USDA ARS, USA	408	111	27.21	348	21.15	297	72.79	6,360	21.41
INRA, France	315	106	33.65	2,338	22.06	209	66.35	4,737	22.67
Russian Academy of Sciences, Russia	265	117	44.15	448	3.83	148	55.85	1,835	12.40
US Geological Survey, USA	256	76	29.69	2,401	31.59	180	70.31	5,412	30.07
University of California-Davis, USA	230	81	35.22	1,499	18.51	149	64.78	3,468	23.28
Tokyo University, Japan	220	63	28.64	1,048	16.63	157	71.36	2,379	15.15
CSIC, Spain	217	64	29.49	1,026	16.03	153	70.51	2,717	17.76
Agriculture and Agricultural Food Canada, Canada	212	68	32.08	995	14.63	144	67.92	1,591	11.05
University Florida, USA	195	71	36.41	982	13.83	124	63.59	2,296	18.52
North Carolina State University, USA	190	57	30.00	750	13.16	133	70.00	3,082	23.17
Cornell University, USA	174	62	35.63	2,001	32.27	112	64.37	3,250	29.02
University of British Columbia, Canada	171	43	25.15	1,165	27.09	128	74.85	4,013	31.35
Illinois University, USA	170	61	35.88	1,425	23.36	109	64.12	2,644	24.26
University of Minnesota, USA	170	57	33.53	1,291	22.65	113	66.47	2,501	22.13
Louisiana State University, USA	166	50	30.12	856	17.12	116	69.88	3,410	29.40
University of Sao Paulo, Brazil	159	43	27.04	712	16.56	116	72.96	1,414	12.19
McGill University, Canada	153	65	42.48	1,031	15.86	88	57.52	1,513	17.19
University of Maryland, USA	150	48	32.00	1,052	21.92	102	68.00	3,011	29.52
Zhejiang University, China	144	45	31.25	371	8.24	99	68.75	442	4.46

Note: TP: total number of articles, SP: single institute articles, CP: inter-institutionally collaborative articles, and TC: total citation count.

Table 4
Top 35 most frequent keywords used during 1991–2010 and in four five-year periods

Keyword	TP	91–10 R (%)	91–95 R (%)	96–00 R (%)	01–05 R (%)	06–10 R (%)
Nitrate	10,837	1 (34.9)	1 (38.8)	1 (38.2)	1 (34.6)	1 (31.6)
Nitrogen	9,332	2 (30)	2 (32.8)	2 (31.3)	2 (29.8)	3 (28.4)
Denitrification	8,732	3 (28.1)	3 (23.8)	3 (28.2)	3 (29.2)	2 (29)
Soil	4,761	4 (15.3)	4 (17.4)	4 (19.3)	4 (16.2)	8 (11.6)
Nitric Oxide	4,587	5 (14.5)	9 (8.9)	5 (13.3)	5 (15.1)	4 (16.5)
Water	3,944	6 (12.7)	5 (11.7)	6 (12)	6 (12.7)	6 (13.5)
Reduction	3,619	7 (11.7)	7 (10.5)	8 (10.9)	7 (11.8)	7 (12.5)
Nitrification	3,220	8 (10.4)	10 (8.3)	9 (10)	8 (10.9)	9 (11)
Removal	2,967	9 (9.6)	27 (3.5)	14 (6)	10 (9.7)	5 (13.9)
Oxide	2,917	10 (9.4)	11 (7.6)	7 (11.8)	9 (10.3)	13 (8.1)
Growth	2,541	11 (8.2)	6 (10.9)	10 (8.6)	12 (7.4)	15 (7.4)
Nitrite	2,409	12 (7.8)	12 (6.1)	11 (7.8)	11 (7.4)	12 (8.6)
Ammonium	2,321	13 (7.5)	8 (9.1)	12 (7.4)	13 (7.3)	16 (7)
System	2,139	14 (6.9)	34 (3.2)	15 (5.6)	14 (7.1)	11 (8.9)
Carbon	2,108	15 (6.8)	14 (4.9)	13 (6.8)	15 (6.8)	14 (7.5)
Wastewater	2,008	16 (6.5)	55 (2.4)	24 (4)	16 (6.6)	10 (10.4)
Model	1,749	17 (5.6)	25 (3.7)	17 (5.2)	17 (6.2)	19 (6.2)
Activated Sludge	1,770	18 (5.3)	49 (2.6)	23 (4.1)	22 (5.1)	18 (6.7)
Oxygen	1,526	19 (4.9)	16 (4.8)	16 (5.4)	18 (5.3)	28 (4.4)
Phosphorus	1,503	20 (4.8)	19 (4.1)	34 (3.6)	21 (5.1)	21 (5.6)
Bacteria	1,487	21 (4.8)	20 (4)	20 (4.5)	23 (4.8)	22 (5.3)
Groundwater	1,482	22 (4.8)	44 (2.8)	28 (3.9)	19 (5.2)	20 (5.8)
Nutrient	1,248	23 (4)	30 (3.4)	25 (4)	25 (4)	29 (4.3)
Dynamics	1,228	24 (4)	47 (2.6)	26 (3.9)	24 (4.7)	33 (4)
Treatment	1,175	25 (3.8)	58 (2.4)	51 (2.7)	26 (3.9)	23 (4.9)
Inhibition	1,170	26 (3.8)	17 (4.2)	19 (4.8)	28 (3.7)	47 (3)
Sediments	1,121	27 (3.6)	32 (3.3)	27 (3.9)	27 (3.8)	43 (3.4)
Plants	1,120	28 (3.6)	15 (4.9)	21 (4.1)	35 (3.4)	49 (3)
Reductase	1,112	29 (3.6)	13 (6.1)	21 (4.1)	29 (3.6)	82 (2.3)
Temperature	1,097	30 (3.5)	48 (2.6)	39 (3.2)	42 (3.1)	27 (4.4)
Acid	1,093	31 (3.5)	24 (3.8)	33 (3.6)	38 (3.3)	41 (3.5)
Kinetics	1,065	32 (3.4)	35 (3)	44 (3)	34 (3.4)	35 (3.9)
Quality	1,011	33 (3.3)	81 (2)	48 (2.7)	32 (3.5)	34 (3.9)
Transport	1,006	34 (3.2)	26 (3.6)	30 (3.7)	40 (3.2)	53 (2.9)
Adsorption	1,003	35 (3.2)	182 (1.2)	76 (2.2)	36 (3.4)	25 (4.5)

Note: TP: total number of keywords and R (%): rank and percentage of keywords in total articles.

Table 5
Most frequently cited articles during 1991–2010

Year	TC	TC/Y	Article/journal	Country
1991	222	11	Nitrate reduction in an unconfined sandy aquifer—water chemistry, reduction processes, and geochemical modeling/*Water Resources Research*	Denmark
1992	181	9	Groundwater nitrate and denitrification in a coastal-plain riparian forest/*Journal of Environmental Quality*	USA
1993	363	20	Increased serum nitrite and nitrate levels in patients with cirrhosis—relationship to endotoxemia/*Hepatology*	UK, Spain
1994	132	8	Nitrate, nitrite and N-nitroso compounds/*European Journal of Pharmacology-Environmental Toxicology and Pharmacology Section*	UK, Netherlands, Germany, USA
1995	237	15	Combined use of groundwater dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in 2 agricultural watersheds, Atlantic Coastal-Plain, Maryland/*Water Resources Research*	USA
1996	204	14	Anaerobic, nitrate-dependent microbial oxidation of ferrous iron/*Applied And Environmental Microbiology*	Germany
1997	215	15	Nitrate removal from drinking water—review/*Journal of Environmental Engineering-ASCE*	Canada
1998	193	15	Xanthine oxidoreductase catalyses the reduction of nitrates and nitrite to nitric oxide under hypoxic conditions/*FEBS Letters*	UK
1999	223	19	Semianalytic moderate-resolution imaging spectrometer algorithms for chlorophyll A and absorption with bio-optical domains based on nitrate-depletion temperatures/*Journal of Geophysical Research-Oceans*	USA
2000	265	24	Genomic analysis of a nutrient response in Arabidopsis reveals diverse expression patterns and novel metabolic and potential regulatory genes induced by nitrate/*Plant Cell*	USA
2001	429	43	Control of nitrogen export from watersheds by headwater streams/*Science*	USA, Spain
2002	225	25	Production of N-2 through anaerobic ammonium oxidation coupled to nitrate reduction in marine sediments/*Applied and Environmental Microbiology*	Denmark
2003	110	16	A mechanism of abiotic immobilization of nitrate in forest ecosystems: the ferrous wheel hypothesis/*Global Change Biology*	USA
2004	150	21	In situ bioreduction of technetium and uranium in a nitrate-contaminated aquifer/*Environmental Science & Technology*	USA
2005	57	11	Chemical conversion of nitrate and nitrite to nitrous oxide for nitrogen and oxygen isotopic analysis in freshwater and seawater/*Analytical Chemistry*	USA
2006	64	13	Emission of N(2)O, N(2) and CO(2) from soil fertilized with nitrate: Effect of compaction, soil moisture and rewetting/*Soil Biology & Biochemistry*	Germany
2007	167	42	Removal of nutrients in various types of constructed wetlands/*Science of the Total Environment*	Czech Republic, USA
2008	142	47	Stream denitrification across biomes and its response to anthropogenic nitrate loading/*Nature*	USA
2009	32	16	Dietary nitrate supplementation reduces the O(2) cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans/*Journal of Applied Physiology*	UK
2010	14	14	Widespread occurrence of nitrate storage and denitrification among foraminifera and gromiida/*Proceedings of the National Academy of Sciences of the United States of America*	Denmark, France, Switzerland, Greenland

Note: TC: total citations of articles from publication to 2010 and C/Y: number of citations/year.

important source of drinking water and sewage and drainage standard has become more and more strictly for total nitrogen, many research and methods were carried out to reduce nitrogen (contain nitrate) from water. The methods are mentioned in Table 4 and mainly are denitrification, reduction, nitrification and adsorption. The leading was the "denitrification" (8,732), which had a large disparity with others, and

whose quantity was more than double that of the "Reduction" (3,619). The higher rank of "denitrification" and "Nitrification" proved researchers' concentration on the biological means for removal. Although "Nitrification" was not the method of nitrate removal, the higher rank was due to the biological method containing two inseparable processes with nitrification and denitrification. This indirectly proved that the biological method was the main method of nitrate removal. It should be noted that the rank and percentage of "adsorption" increased steeply from #182 (1.2%) during 1991–1995 to #25 (4.5%) during 2005–2010, indicating researchers' concentration on the adsorption method for nitrate removal during the last twenty years.

Numerous products were formed during nitrate removal, among which nitrogen was the most predominant. Nitrogen was the ideal product of nitrate removal as it is environmentally friendly [38]. However, some by-products were produced, such as nitric oxide, nitrite, and ammonium. Nitrite and ammonium can be removed by the nitrate treatment process or subsequent treatment process before they polluted the environment [39]. Most of nitric oxide may transfer to the atmosphere, which is harmful to environment. Nitrous oxide is a greenhouse gas and its effect on the global climate warming is becoming increasingly significant, which has caused great concern to scientists [40,41]. An important reason for acid rain and photochemical smog are nitric oxide and nitrogen dioxide [17,42]. Therefore, nitric oxide became the hot issue (rank: 5) and continued to rise, from #9 (8.9%) during 1991–1995 to #4 (16.5%) during 2005–2010.

3.5. Most cited articles

The time-dependence of citations might be informative for tracking the impact of an article. Table 5 shows the most frequently cited articles of nitrate removal in each year since publication through 2010. Two were published in *Nature* (IF = 31.434 in 2009) and *Science* (IF = 28.103 in 2009), respectively. Six were published in environment field. Among the most frequently cited articles each year, eleven articles included authors from the USA, four from the UK, three from both Germany and Denmark. From 1991 to 2010, the most frequently cited article was "Control of nitrogen export from watersheds by headwater streams", which was published in Science by Peterson from USA in 2001 and had been cited 429 times by 2010. It was always accompanied with removal of other substances when removing nitrate, as shown in 2000, 2001, and 2007 articles. Among the 20 most cited articles, six were about biological denitrification and two were about chemical reduction. "Stream denitrification across biomes and its response to anthropogenic nitrate loading" had the highest average number of citations by 2010, indicating the focus of nitrate removal research on the biological method and consistent with previous results. In addition, the nitrate removal distributed in various fields, such as groundwater, wastewater, soil, forest, seawater, and marine sediments.

4. Conclusions

In this study, we provide an alternative perspective on the global research trends in nitrate removal. A bibliometric analysis of the patterns of publication outputs, journal and subject categories, country and institutional distributions, the distribution and changes of words in article titles, author keywords, KeyWords Plus, and most-cited articles were conducted. A total of 2,961 journals were listed in the 174 SCI subject categories. Water Research published the most articles (690). The subject category "environmental sciences" had the greatest number of output and the most rapid growth since 1994, indicating a research emphasis on the interactional relationship between nitrate and environmental problems.

At the country level, the USA had a dominant position in nitrate removal research by contributing the most total articles, single-country articles, and internationally collaborative articles. China had the highest growth rate in the number of articles since 2001 and ranked second in 2006. Chinese Academy of Sciences, USDA ARS, INRA and Russian Academy of Sciences, Russia, and US Geological Survey were the five most productive institutions. Additionally, inter institutional collaborations were more prevalent than single institutes. Analysis of the most cited articles revealed that nitrate removal distributed in various fields while the biological was the main method.

A new bibliometric method—"word cluster analysis", through synthetically analyzing the distribution and changes of words in article titles, author keywords, KeyWords Plus, could help researchers realize the development of nitrate removal research and establish future research directions.

It can be concluded that the main field of nitrate removal was soil and water. However, the research in the soil field gradual decreases, on the contrary, an increase in the water field appears gradually, especially in wastewater. Biological method will continue to be the leading research methods. The product of

nitric oxide will continue to be the research hotspot due to its harm to the environment.

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