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A global perspective of bioaccumulation research using bibliometric analysis

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Contaminant bioaccumulation has long been used as a key indicator of the potential risk and toxic effects of contaminants to the environment and human health. In the present study, a bibliometric analysis based on the Science Citation Index Expanded from Thomson Reuters' Web of Science Core Collection was carried out to gain insights into research activities and tendencies of global bioaccumulation from 1991 to 2014. Study emphases included performance of annual outputs, countries, institutions, Web of Science categories, journals, research hotspots, and articles with lasting impacts. Results indicated that annual outputs of the bioaccumulation articles increased steadily in 1991 to 2014. USA dominated the bioaccumulation field, followed by China, Canada, and France. Government agencies, such as Environment Canada and the US Environmental Protection Agency were the leading institutions in bioaccumulation research. The most prolific and promising category was environmental science, which was significantly ahead of other categories, such as toxicology, marine and freshwater biology, as well as environmental engineering. The bioaccumulation articles were dispersed in 1,267 journals, whereas half of the articles reside on 19 core journals. Research focuses and hot issues in the bioaccumulation field were evaluated by word cluster analysis. Toxic effects, exposure, risk analysis and/or assessment, as well as bioavailability of chemicals, are major concerns in the bioaccumulation field. Metals, such as mercury, cadmium, copper, lead, and arsenic, were contaminants of greatest concern, among which mercury was the most studied. Persistent organic pollutants, such as polychlorinated biphenyl, polycyclic aromatic hydrocarbons, and organochlorine compounds, were also very significant in the study of bioaccumulation. Substances with lasting impact were evaluated by citation lives of top articles. Perfluorooctane sulfonate and methylmercury have lasting impacts for their unusual routes in bioaccumulation. Moreover, methodological innovations in acquiring food chain position with stable nitrogen isotopes played an important role in bioaccumulation research.

Keywords: *Bioaccumulation, Sci-Expanded, Bibliometrics*

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1. Introduction

Bioaccumulation has been both a scientific and political concern. Many bioaccumulative chemicals, such as perfluorinated compounds, polybrominated diphenyl ethers, and phthalates, which are widely used in everyday life, have become ubiquitous environment contaminants. Per the Science Citation Index Expanded^{TM} (SCI-EXPANDED), bioaccumulation phenomenon of chemicals in food chains was first demonstrated in 1958 [1]. The paper illustrated that the moderate application of dichlorodiphenyltrichloroethane in an elm's grove was strengthened by earthworms and produced a lethal effect on robins nearly one year later [1]. In the 1960s, Rachel Carson's book "Silent Spring" started an era of research on bioaccumulation in food chains. Early research in bioaccumulation focused on tests for evaluating the bioaccumulation extent of chemicals and heavy metals in various flora and fauna species, such as ciliated protozoans [2], algal species [3], oyster [4], and fish [5]. Factors, including octanol-water partition-coefficient of chemicals [6] and lipid pool size of the organisms [5] as well as uptake and clearance kinetics [7], which affecting the bioaccumulation extent of contaminants in organisms were also discussed extensively. In the 1980s, risk assessment and toxicological analysis based on bioaccumulation were used in determining water and sediment quality criteria. In the last 20 years, assessing bioaccumulation has become a component of international efforts to identify and to control chemicals of environmental concern. International agreements, such as the Stockholm Convention on Persistent Organic Pollutants and Minamata Convention on Mercury, have been endorsed by numerous nations to identify, ban, or regulate the world's most persistent, bioaccumulative, and toxic substance. Bioaccumulation-related research has also been a multidisciplinary field, covering a wide spectrum, including studies on environmental sciences [8, 9], toxicology [10], and biology [11]. Nowadays, several problems in bioaccumulation research exist, for instance, bioaccumulative substances, which demonstrate an appreciable concentration increase in food chains. In addition, given that the consumptions of organisms contaminated by bioaccumulative chemicals exposes the consumer to high dosages of toxic chemicals [12, 13], the toxic responses and exposure sources of organisms to bioaccumulative substances were also discussed extensively [14]. With the importance and complexity of bioaccumulation research, the portrayal of the global science performance in this field is necessary.

Bibliometrics is a useful tool for mapping literature around a research field. Bibliometrics has been carried out for mapping hot spots and research trends in many environmental topics, such as drinking water [15], aerosol [16], volatile organic compounds [17], and estuary pollution [18]. Furthermore, bibliometric analysis revealed bioaccumulation as one of the most active topics in estuary pollution research [18]. In the present study, the current state of bioaccumulation research performance was analyzed based on 11,367 articles published in SCI-EXPANDED (Web of Science, Thomson Reuters, New York, NY) from 1991 to 2014, providing an overview of the annual outputs, leading countries and institutions, subject categories, and mainstream journals and focusing particularly on research hotspots and tendencies. Furthermore, based on bibliometric results, the historical research review revealed by the top articles was also presented in this study.

2. Methodology

Data were obtained from the online version of SCI-EXPANDED databases of the Web of Science Core Collection of Thomson Reuters (updated on July 25th, 2015). According to Journal Citation Reports (JCR) of 2014, the topic of an article was recognized as the combination of titles, author keywords, KeyWords Plus, and abstract. The keywords bioaccumulat*, "bio-accumulat*", bioconcent*, and "bio-concent*" were used in terms of topic within the publication year of 1991 to 2014. Detailed descriptions of the keywords are provided in Table 1. Given that original articles are the major peer-reviewed document type directly proposing novel concepts and presenting substantive findings, the article was the only document type considered. KeyWords Plus supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the Thomson Reuters database, and substantially augments title–word and author–keyword indexing [19]. Another filter, the "front page", meant that only the articles with the search keywords, including article title, abstract, and author keywords, in their "front page" were preserved [20]. The articles that could only be searched by *KeyWords Plus* were excluded. Web of Science Core Collection full record and number of citations in each year for each article were downloaded into Microsoft Excel 2010 and additional coding of the downloaded records was manually performed [21]. Starting from the year of publication, the citation frequencies for each article per year were collected until 2014. The total citation number of articles cited in 2014 was recorded as C_{2014} and the total number of times an article was cited from its publication until 2014 was recorded as TC_{2014}. The citations per publication (CPP) values of the articles were defined as CPP = TC_{2014}/year [21]. Impact factors (IF2014) were taken from the JCR published in 2014.

Contributions of different institutions and countries were estimated by the affiliation of at least one author to the publications [22]. The collaboration types of countries and institutions were analyzed and ranked by several bibliometric indicators, such as "total articles" (TP), "independent articles" (IP), "international collaborative articles" (ICP), and "national collaborative articles" (NCP) [23]. The collaboration types of institutions were further demonstrated by the percentage ratios of collaboration types (IP: NCP: ICP) to their respective total articles. The publication authorship patterns for countries and institutions were illustrated by their rank and percentage of "first authored articles" (FP), "corresponding authored articles" (RP), and "single authored articles" (SP) [15].

3. Performance of Publication

3.1. *Languages and annual performance*

A total of 11,367 articles met the selection criteria in SCI-EXPANDED. Ninety-nine percent of the articles were published in English. Thirty-nine percent of the 163 non-English

Table 1
Description of keywords.

Keywords	Related keywords
bioaccumulat*	bioaccumulation, bioaccumulative, bioaccumulate, bioaccumulated, bioaccumulating, bioaccumulates, bioaccumulatd, bioaccumulator, bioaccumulators, bioaccumulati, bioaccumulativeness, bioaccumulatiom, bioaccumulatiory, bioaccumulatory, bioaccumulatable
"bio-accumulat*"	"bio-accumulation", "bio-accumulate", "bio-accumulative", "Bio-accumulator", "bio-accumulativeness", "bio-accumulating", "bio accumulated", "bio-accumulates ", "bio-accumulators ", "bio-accumulatable", "bio-accumulativity"
bioconcent*	bioconcentration, bioconcentrate, bioconcentrating, bioconcentrates, BioConcentrationFactors, bioconcentrated, bioconcentraction, bioconcentraion, bioconcentrations, bioconcentrator, bioconcentratable, bioconcentrators, bioconcentrace
"bio-concent*"	"bio-concentration", "bio concentrated", "bio-concentrate", "bio concentrations", "bio-concentrators", "bio-concentrator"

articles in the bioaccumulation field had no citations (TC_{2014} = 0). The most frequently cited non-English article entitled "Bioaccumulation of metals within the hydrothermal mytilidae Bathymodiolus sp. from the Mid-Atlantic Ridge" [24] was published in French with a TC_{2014} = 42 compared with the English article with the maximum TC_{2014} value of 1,084 [8].

An overview of bioaccumulation publications from 1991 to 2014 is illustrated in Fig. 1. The annual outputs increased from 140 in 1991 to 1,096 in 2014. The annual outputs rose more rapidly in 2008 to 2014 than in 1991 to 2007. Meanwhile, the foundation-supporting percentage of articles in 2008 to 2014 was 69% (4,175 out of 6,023articles) compared to the percentage in 1991 to 2007 was 1.8% (10 out of the 5,344 articles). The average annual CPP from 1991 to 2004, with values ranging from 25 to 37, was 31, whereas the articles published in the last ten years have lower CPP values ranging from 0.52 to 29.

3.2. *Countries and institutions*

The articles were published by 28,352 authors from 131 countries, except for 18 articles with no affiliations. The top 12 countries listed in Table 2 published 84% of the 11,349 articles (9,574 articles). Each of the 12 countries published more than 300 articles. The annual outputs of China were compared with the Group of Seven (G7) countries (USA, Canada, France, the UK, Italy, Germany, and Japan) and are shown in Fig. 2. China published the very first bioaccumulation research article in 1991 [25], which was 33 years later than the first article published by USA in 1958 [1]. China was ranked as the top publishing country with a total annual output of 221 in 2014. This notable increase might be attributed to the large-scale foundations initiated by the Chinese government. China published the biggest share of foundation-supporting articles (66%), followed by France with a share of 62%,

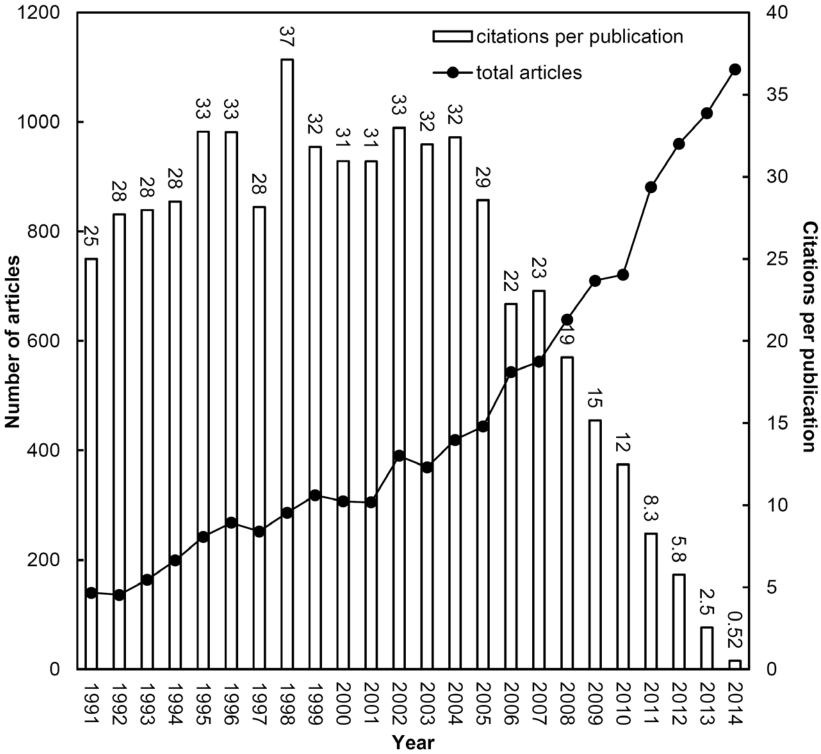

Figure 1

Annual number of articles and citations per publication by year.

whereas the other countries had lower average foundation-supporting share of 31%. Furthermore, the Chinese central government recently issued a document about strengthening the monitoring of bioaccumulative and persistent substances in soil; thus, the Chinese outputs might maintain this growing trend in the near future.

The top ten institutions are ranked by article counts in Table 3. All the 10 institutions are found in the top 12 countries. The rank and percentage distributions of FP and RP of the top ten institutions were almost the same, implying that the first author and the corresponding author possibly came from the same institute. The Chinese Academy of Sciences, with 420 articles, ranked first in terms of six indicators, including TP, IP, ICP, NCP, FP, and RP. However, bias was shown, because the Chinese Academy of Sciences has over 100 branches in different cities. At present, the publications of the institute are pooled under one heading, and publications divided into branches result in different rankings. The second highest ranking institution was Environment Canada, which conducts and publishes 87% of the research in collaboration with external researchers. Stockholm University in Sweden showed a maximum ICP percentage of 63%, indicating its high level of international collaborative investigation. The University of Gdańsk in Poland exhibited independence with

Table 2

The top 12 most productive countries (TP > 300).

Country	TP	TP R (%)	IP R (%)	ICP R (%)	FP R (%)	RP R (%)	SP R (%)
USA	2695	1 (24)	1 (22)	1 (32)	1 (20)	1 (20)	1 (28)
China	1223	2 (11)	2 (10)	4 (13)	2 (10)	2 (10)	8 (3.1)
Canada	1147	3 (10)	3 (7.8)	2 (19)	3 (7.9)	3 (7.9)	3 (6.1)
France	764	4 (6.7)	4 (5.5)	5 (12)	4 (5.5)	4 (5.6)	7 (3.6)
Spain	574	5 (5.1)	6 (4.2)	7 (8.5)	6 (4.2)	6 (4.1)	34 (0.42)
India	550	6 (4.8)	5 (5.4)	22 (2.4)	5 (4.5)	5 (4.5)	8 (3.1)
UK	545	7 (4.8)	9 (2.6)	3 (13)	9 (3.0)	9 (3.0)	6 (4.8)
Italy	538	8 (4.7)	7 (4.1)	8 (7.3)	7 (4.1)	7 (4.1)	11 (2.3)
Germany	510	9 (4.5)	8 (2.8)	6 (11)	8 (3.1)	8 (3.2)	4 (5.6)
Netherlands	367	10 (3.2)	12 (2.4)	10 (6.6)	12 (2.4)	12 (2.3)	13 (2.1)
Japan	333	11 (2.9)	11 (2.4)	14 (4.9)	11 (2.4)	11 (2.4)	16 (1.5)
Poland	328	12 (2.9)	10 (2.5)	15 (4.5)	10 (2.7)	10 (2.7)	2 (6.3)

TP: total number of articles; TP R (%): rank and the percentage of total articles; IP R (%): rank and the percentage of independent articles; ICP R (%): rank and the percentage of international collaborative articles; FP R (%): rank and the percentage of first authored articles; RP R (%): rank and the percentage of the corresponding authored articles; SP R: rank and the percentage of the single authored articles.

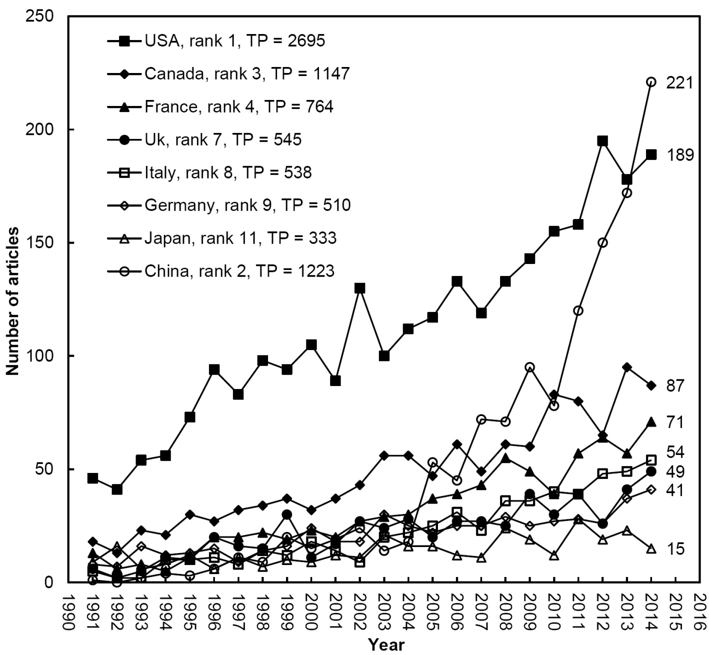

Figure 2

Publications of G7 and China during 1991-2014.

Table 3

The top ten most productive institutions.

Institution	TP	TP R (%)	IP R (%)	ICP R (%)	NCP R(%)	FP R (%)	RP R (%)	SP R (%)	IP (%)	ICP (%)	NCP (%)
Chinese Academy of Science, China	420	1 (3.7)	1 (2.5)	1 (5.0)	1 (4.3)	1 (2.7)	1 (2.7)	N/A	115 (27)	115 (27)	190 (45)
Environment Canada, Canada	268	2 (2.4)	8 (0.73)	2 (4.5)	3 (3.0)	3 (0.97)	3 (1.0)	2 (1.5)	34 (13)	102 (38)	132 (49)
US EPA, USA	257	3 (2.3)	2 (1.4)	4 (2.3)	2 (3.2)	2 (1.3)	2 (1.3)	1 (4.0)	66 (26)	52 (20)	139 (54)
US Geological Survey, USA	181	4 (1.6)	4 (1.0)	10 (1.6)	4 (2.3)	4 (0.88)	4 (0.9)	3 (1.0)	45 (25)	37 (20)	99 (55)
Spanish National Research Council, Spain	125	5 (1.1)	11 (0.58)	6 (2.0)	7 (1.2)	7 (0.61)	8 (0.61)	N/A	27 (22)	45 (36)	53 (42)
Fisheries and Oceans Canada, Canada	124	6 (1.1)	34 (0.3)	13 (1.5)	5 (1.7)	11 (0.48)	14 (0.46)	N/A	14 (11)	34 (27)	76 (61)
University of Bordeaux 1, France	117	7 (1)	6 (0.83)	23 (1.1)	7 (1.2)	6 (0.63)	6 (0.63)	8 (0.63)	39 (33)	25 (21)	53 (45)
Stockholm University, Sweden	105	8 (0.93)	17 (0.49)	3 (2.9)	77 (0.37)	16 (0.46)	11 (0.47)	N/A	23 (22)	66 (63)	16 (15)
University of Gdańsk, Poland	104	9 (0.92)	4 (1.0)	6 (2.0)	90 (0.32)	5 (0.82)	5 (0.84)	5 (0.84)	45 (43)	45 (43)	14 (13)
National Oceanic and Atmospheric Administration, USA	102	10 (0.9)	17 (0.49)	36 (0.87)	6 (1.3)	11 (0.48)	16 (0.45)	23 (0.42)	23 (23)	20 (20)	59 (58)

TP: total number of articles; TP R (%): rank and percentage of total articles; IP R (%): rank and percentage of single institution articles; ICPR (%): rank and percentage of international collaborative articles; NCP R (%): rank and percentage of nationally collaborative articles; FPR (%): rank and percentage of first author articles; RP R (%): rank and percentage of corresponding authored articles; SP R (%): rank and percentage of single author articles. IP (%): number of single institution articles and percentage of single institution articles in the total institution articles; ICP (%): number of internationally collaborative articles and percentage of internationally collaborative articles in the total institution articles; NCP (%): number of nationally collaborative articles and percentage of nationally collaborative articles in the total institution articles.

a maximum percentage of 43% for single-institution articles. Moreover, author information indicated that J. Falandysz from the Department of Environmental Chemistry and Ecotoxicology of the University of Gdańsk contributed 72 articles on his own and ranked second among all the authors. The most prolific author, who contributed a total of 97 articles, was W.X. Wang from Hong Kong University of Science and Technology.

3.3. *Web of Science Categories and Journals*

Bioaccumulation articles are distributed among 140 subject categories. The annual publications of the top six productive subject categories from 1991 to 2014 are displayed in Fig. 3. Environmental science contributed the most with 7,388 (65%) articles, followed by toxicology marine and freshwater biology, and environmental engineering, with 3,017 (27%), 1,264 (11%), and 1,198 (11%) articles, respectively. However, 65 (46%) categories each contributed less than ten articles, and 20 (14%) categories each contributed only one article. Diversity of the 20 least productive categories, such as psychology, mechanics, and medical laboratory technology, etc., suggests the breadth of bioaccumulation research.

Several core journals were observed to contribute a large percentage of articles. The 19 most prolific journals, each of which produced more than 100 articles, are shown in Table 4 with the number of total articles and impact factors. Environmental Toxicology and Chemistry ranked first with 880 articles (7.7% of 11,367 articles), and Environment International ranked 19th with the highest IF of 5.559. Besides, Aquatic Toxicology ranked seventh was the only journal not under the environmental science category. Meanwhile, 619 (49% of the total 1,267) journals published only 1 article each.

4. Hot issues and topics of lasting impacts

4.1 *Hot issues*

Among the 11,367 articles with titles, 8,898 articles (78%) had record information of author keywords, 11,248 (99%) had abstract information. Based on analyzing the number of publications containing the word clusters in their word base which were composed with words in articles titles, author keywords and abstract, the overview of the research hotspots could be revealed. Based on the bibliometric results, "toxic" effects, "bioavailability", "exposure" and "risk" analysis and/or assessment of chemicals attracted great concern in the bioaccumulation field. A total of 4,348 articles (37% of the total articles) focused on toxic effects. Toxicity terms involved in bioaccumulation field were toxicity (2,389 articles; 21% of the total articles), phytotoxicity (105; 0.9%), genotoxicity (99; 0.9%), etc. Toxicological (513; 4.5%) and ecotoxicological (230; 2%) analysis as well as toxicokinetics (151; 1.3%) of the bioaccumulation of chemicals were also of significant concern. Moreover, 1,242 articles (11% of the total articles) used fish (as well as the related words fish, zebrafish, fishes, and catfish) in their studies, indicating that fish species are commonly used to determine the possible association between the toxic effects of contamination and human health. Exposure-related research occupied the second position with 3,239 articles (30% of the total articles). Exposure sources (466 articles; 4%) and/or routes (252 articles; 2.2%) were primary issues which were discussed extensively. Furthermore, bioaccumulation exposure markers (309 articles; 2.7%), which can reflect the distribution of a chemical in an organism, are factors of main concern. Much research on bioaccumulation (1,676 articles; 15%) was conducted for a complete assessment of its risks to humans and wildlife. And bioavailability, which refers to the uptake of chemicals by living organisms, was also discussed extensively (1,289 articles; 11%).

Metals were the most frequently studied bioaccumulation substances by word occurrence frequency. Aside from "bioaccumulation," which was the search keyword in this study, metals (as well as the keywords metal, heavy metals, and heavy-metals) ranked first in terms of words in title and author keywords. In terms of author keywords, mercury and

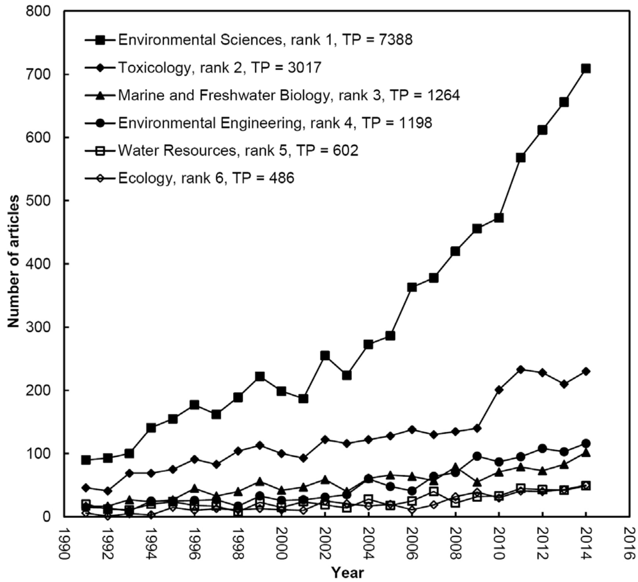

Figure 3

Publications of the top 6 productive Web of Science categories during 1991-2014.

Table 4

The 19 core journals taking 52% of articles with the number of articles and impact factor.

Journal	TP (%)	IF_{2014}
Environmental Toxicology and Chemistry	880 (7.7)	3.225
Chemosphere	741 (6.5)	3.340
Environmental Science and Technology	656 (5.8)	5.330
Science of the Total Environment	507 (4.5)	4.099
Environmental Pollution	435 (3.8)	4.143
Ecotoxicology and Environmental Safety	329 (2.9)	2.762
Aquatic Toxicology	314 (2.8)	3.451
Archives of Environmental Contamination and Toxicology	284 (2.5)	1.895
Marine Pollution Bulletin	259 (2.3)	2.991
Environmental Monitoring and Assessment	220 (1.9)	1.679
Bulletin of Environmental Contamination and Toxicology	202 (1.8)	1.255
Water Air and Soil Pollution	184 (1.6)	1.554
Environmental Science and Pollution Research	170 (1.5)	2.828
Ecotoxicology	130 (1.1)	2.706
Fresenius Environmental Bulletin	124 (1.1)	0.378
Marine Environmental Research	123 (1.1)	2.762
Journal of Hazardous Materials	120 (1.1)	4.529
Water Research	104 (0.91)	5.528
Environment International	102 (0.9)	5.559

TP: total number of articles; %: the percentage of articles of journals in total articles; IF2014: impact factor in 2014.

other related words (Hg, methylmercury, monomethylmercury, total mercury, inorganic mercury, organic mercury, mercury ion, and mercury compounds) (830; 9.3%), cadmium (510; 5.7%), copper (283; 3.2%), lead (260; 2.9%), and arsenic (214; 2.4%) are metals of great significance. Several other metals, such as zinc (205; 2.3%), chromium (124; 1.4%), selenium (149; 1.7%), and nickel (82; 0.9%) were also discussed frequently. Words in author keywords relating to organic pollutants were as follows: polychlorinated biphenyl (220; 2.5%), polycyclic aromatic hydrocarbons (176; 2.0%), organochlorine compounds (205; 2.3%), and persistent organic pollutants (198; 2.2%). In addition, perfluorinated chemicals (159; 1.8%), polybrominated diphenyl ethers (115; 1.3%), and nanoparticles (100; 1.1%), all three of which were also the topics of leading articles in 2014 (C_{2014}>40), were substances of new concern [8, 26, 27].

4.2. *Topics of lasting impacts*

Topics of the top articles in both C_{2014} and TC_{2014} were substances of lasting impacts. The citation lives of the top ten articles in both C_{2014} and TC_{2014} are displayed in Fig. 4. Each of the four articles published for more than ten years had a C_{2014} greater than 40 and a TC_{2014} greater than 400.

The most cited article [8] was published in 2001 with a TC_{2014} of 1,020 and an annual growth rate of 73. The article reported the global distribution of perfluorooctane sulfonate (PFOS) in wildlife tissues for the first time. Result demonstrated that concentrations of PFOS are higher in animals from relatively more populated regions than those in animals from remote marine locations, and greater in predatory animals, such as minks and bald eagles, than their diets, indicating that PFOS bioaccumulates in higher trophic levels of the food chain [8]. Meanwhile, a series of field tests confirmed the bioaccumulative nature of PFOS in mammals and birds [28, 29]. However, laboratory tests in fish showed that PFOS is not bioaccumulative [30]. In 2007, Kelly et al. revealed that chemicals, such as PFOS, with a low octanol–water partition coefficient ($K_{OW} < 10^5$) and a high octanol–air partition coefficient ($K_{OA} \geq 10^6$), are another class of bioaccumulative substances, which do not biomagnify to high levels in aquatic food webs but in food webs including air-breathing animals, such as humans and birds [31]. Thus, earlier assumptions that bioaccumulative substances are hydrophobic and fat-soluble chemicals having high octanol–water partition coefficients ($K_{ow} \geq 10^5$) [32, 33, 34] were corrected. Kelly et al. proposed that these low K_{OW}–high K_{OA} chemicals need to be assessed by regulatory authorities [31]. In 2009, PFOS and related compounds were added into the Annex B of the Stockholm Convention on Persistent Organic Pollutants to restrict or to eliminate their production and use.

The article of Cabana and Rasmussen focused on the comparison of food chains using stable nitrogen isotopes ($\delta^{15}N$, $\delta^{14}N$) [35]. The abundance ratio of stable nitrogen isotopes (δ15N:δ14N) in organisms occupying successive levels in food chains was first revealed by Miyake and Wada in 1967 [36]. The $\delta^{15}N$:$\delta^{14}N$ was used extensively to examine the structure and dynamics of food webs as well as contaminant bioaccumulation in aquatic food webs [11, 37]. However, the differences in δ15N at the base of food chains lead to confusion in cross-system comparisons [37, 38]. Cabana and Rasmussen first reported that the

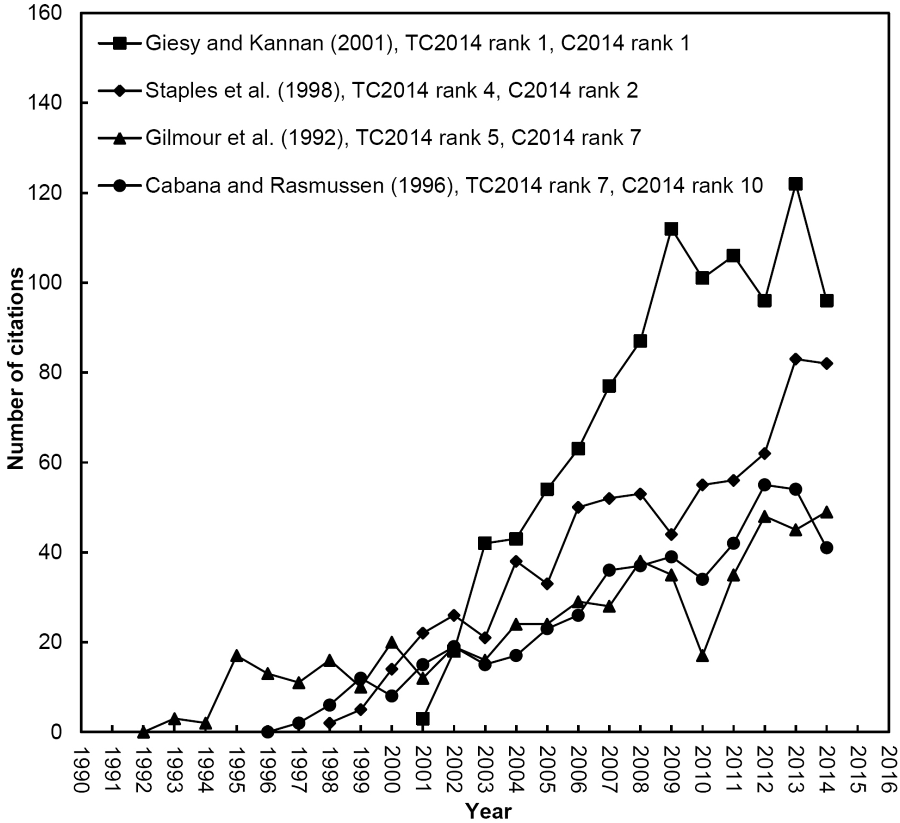

Figure 4

Article lives of the top ten articles in both C_{2014} and TC_{2014}.

variation in food chains leading up to the fish level could be limited to only one trophic level by correcting the baseline variation of δ15N using the large primary consumers, provided that the δ15N in those organisms are stable except for when influenced by anthropogenic nutrient inputs [35]. In the following year, the ability of baseline-adjusted $\delta^{15}N$ to represent the trophic positions of aquatic consumers was confirmed by Van der Zanden et al. [39]. The method was further corrected by fitting a logistic curve to the isotope values of primary consumers in the $\delta^{15}N$–$\delta^{13}C$ bi-plot and using the baseline relationship $\delta^{15}N$–$\delta^{13}C$, as well as the δ15N and δ13C values of the consumer to estimate trophic position [40]. In 2002, a more general solution was developed by using a two-ended member mixing model to create a baseline from which trophic position could be calculated [41].

The earliest article was published in 1992 and focused on mercury methylation in freshwater sediments [42]. Mercury is a metal of greatest concern in the bioaccumulation field, as illustrated in Section 4.1. Almost all of the mercury deposited from the atmosphere is in inorganic form, whereas the metal predominantly accumulates in the food chain as methylmercury [43]. An earlier assumption was that methanogenic bacteria play a major role in methylmercury production [44]. However, Gilmour et al. revealed that sulfate-reducing bacteria are important mediators of mercury methylation in lacustrine sediments and provide a possible mechanism for increased methylmercury bioaccumulation in water bodies affected by increased sulfate deposition [42].

The paper by Staples et al. was actually a review paper which illustrated the environmental fate, effects, and exposures of bisphenol A (BPA) [45], but it was misclassified as an article in the Web of Science database. Since the paper documented background information and comprehensive summary on the research status of BPA, it has been cited frequently.

5. Conclusions

Bioaccumulation research increased sharply from 1991 to 2014. USA, China, Canada, and France are the leading countries that contributed most of the independent and international collaborative articles. Given the importance of bioaccumulation research in environmental regulation making, most of the leading institutions were government agencies, such as Environment Canada, US EPA, etc. Studies on environmental science, toxicology, marine and freshwater biology, and environmental engineering were observed to gradually reduce the bioaccumulation of substances. More than half of the total outputs are found in 19 core journals in the category of environmental science. However, the citation numbers of the output showed high independence with the IF of the journal.

Research focusing in the bioaccumulation field was evaluated with information analyzed by word cluster analysis. Toxic effects, exposure, and risk analysis/assessment, as well as bioavailability of chemicals are major concerns in bioaccumulation studies and are still gaining popularity. Metals and organic pollutants, which are toxic and persistent in the environment, are primary issues based on their occurrence frequencies in the topic words. Citation life cycles of top articles, both in total citations and annual citation in 2014, were evaluated, and the causes of their lasting impacts were analyzed. Results showed that both PFOS and methylmercury are contaminants, which bioaccumulate in organisms via different routes from previously proposed hypotheses. In addition, methodological innovations in identifying food chain position with stable nitrogen isotopes are milestones in the acquisition of bioaccumulation factors. The top article analysis has been proven to be an effective approach for revealing articles with valuable innovative ideas and could also be adapted in other studies for uncovering creative ideas in a given research field.

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