Environ Sci Pollut Res (2017) 24:26079–26091
DOI 10.1007/s11356-017-0147-3

RESEARCH ARTICLE

Characteristics and trends on global environmental monitoring research: a bibliometric analysis based on Science Citation Index Expanded

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Received: 4 May 2017 / Accepted: 7 September 2017 / Published online: 24 September 2017

Abstract A bibliometric analysis based on the Science Citation Index Expanded from Web of Science was carried out to provide insights into research activities and trends of the environmental monitoring from 1993 to 2012. Study emphases covered publication outputs, language, categories, journals, countries/territories, institutions, words, and hot issues. The results indicated that the annual output of environmental monitoring publications increased steadily. The environmental sciences and analytical chemistry were the two most common categories. *Environmental Monitoring and Assessment* published the most articles. The USA and the UK ranked in the top two in terms of all five indicators. The U.S. Environmental Protection Agency took the leading position of the institutions in terms of publication output. The synthesized analysis by words in title, author keywords, and *KeyWords Plus* provided important clues for hot issues. Researchers paid more attention on water environment monitoring than other environmental factors. The contaminants including organic contaminants, heavy metal, and radiation were most common research focuses, and the organic contaminants and heavy metal of the degree of concern were gradually rising. Sensor and biosensor played an important role in the field of environmental monitoring devices. In addition to conventional device detection method, the remote sensing, GIS, and wireless sensor networks were the mainstream environmental monitoring methods. The international organization, social awareness, and the countries' positive and effective political and policies promoted the published articles.

Keywords Environmental monitoring · Keyword · Global research hot issues · SCI-Expanded · Bibliometric

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Introduction

The Conference on the Human Environment, held in Stockholm during the period June 5–16, 1972, was the first international conference of governments around the world to discuss environmental issues and to explore strategies to protect the global environment (Christopher and Barthel 1972). Environmental monitoring is defined as a time series of measurements of physical, chemical, and biological variables, designed to answer questions about environmental change. It is a fundamental component of environmental science and policy (Lovett et al. 2007). As a tentative assessment of applicable technology, the nature of the environmental monitoring task was discussed in 1971 I.E. Region 2 Conference on Technology Forecasting and Assessment of Electrotechnology (Hanson et al. 1971). The Global Environmental Monitoring System (GEMS), a part of the United Nations Environment Program (UNEP), was established in 1975. The purpose of the GEMS is to provide early warning of impending natural or man-induced environmental changes or trends that threaten direct or indirect harm to human health or well-being. The early environmental monitoring activities focused on the nuclear and radiation related to the accident, handling of radioactive materials, and the public health in the beginning of 1960s, such as accidental deposition of radioactivity after the Windscale accident of October 1957 (Chamberlain et al. 1961), low-activity radioactive waste from the Windscale Works to the Irish Sea (Dunster et al. 1964), principles of environmental monitoring related to handling of radioactive materials (Wheatley 1967), and radiation levels of protecting plant personnel from any hazard which might occur (Selby et al. 1961). The measurements and risk assessments of chemical contaminants in environment have long been a subject of public concern. To provide the first nationwide reconnaissance of the occurrence of organic wastewater contaminants (OWCs), the U.S. Geological Survey used five newly developed analytical methods to measure concentrations of 95 OWCs in water samples of 139 streams across 30 states during 1999 and 2000 (Kolpin et al. 2002). Multivariate statistical and GIS-based approach to identify heavy metal sources in soils were discussed (Facchinelli et al. 2001). Biomonitoring of exposure to chemical warfare agents and polyfluoroalkyl substances were presented (Noort et al. 2002; Houde et al. 2006). A wide array of bioaccumulation markers and biomarkers, used to demonstrate exposure to and effects of environmental contaminants, has been discussed in relation to their feasibility in environmental risk assessment (van der Oost et al. 2003). With respect to analytical methods, portable, rapid, and sensitive biosensor technologies with immediate "on-the-spot" interpretation of results showed particular promise in environmental monitoring (Ivnitski et al. 1999). The remote sensing (Benz et al. 2004), GIS (Facchinelli et al. 2001), and wireless sensor networks (Yick et al. 2008) have been widely applied as basic approaches in environmental monitoring since the twenty-first century.

Bibliometric methods have been used as the common research instruments to measure scientific progress in various disciplines of science (van Raan 1996; Nederhof 2006; Fu et al. 2013). Since the concept of "evaluative bibliometrics" was proposed (Narin et al. 1976), many scientists have tried to evaluate the distribution patterns of articles of language, journal, category (Garcia-Rio et al. 2001; Zhou et al. 2007), institution (Van Raan 2005a), and country (Pouris 2007). However, traditional bibliometric analysis did not give enough clues for the research focuses and trends. Covering more than simply publication data would allow us to gain a deeper insight into important aspects of research performance (van Raan 2005b). The frequency of keyword analysis has been quantitatively analyzed to identify the leading fields of research (Mela et al. 1999). The title, along with the author keywords, provides a reasonably detailed picture of the article's theme, while *KeyWords Plus* generated independently of the title or author keywords, describing the article's contents with greater depth and variety (Garfield 1990). The analysis including words in title, author keywords, and *KeyWords Plus* together could reduce the influence of some limitations, such as the uncompleted meaning of single words in title, the small sample size for author keywords, and the indirect relationship between *KeyWords Plus* and the research emphases (Fu and Ho 2013). In the latest decade, more information, closer to the research itself, the paper title, author keywords, *KeyWords Plus*, and words in abstracts (Li et al. 2009a; Zhang et al. 2010) have been employed to reveal research trends.

Bibliometric method was used to analyze the global development of the environmental monitoring research field. The environmental monitoring-related research papers from 1993 to 2012 were comprehensively analyzed to understand the global research situation. The analyzed aspects referred to the quantitative description of outputs, language, Web of Science categories, journals, countries/territories, and institutions of publications. Another focus was to reveal the hot issues from words analyzing in paper title, author keywords, and *KeyWords Plus*.

Methodology

The information of documents used in this study was based on the Science Citation Index Expanded (SCI-Expanded) of Web of Science in the Thomson Reuters (updated on 10 July 2013). There were 5188 documents from 1993 to 2012 with keywords "environmental monitoring," "environmental monitors," and "environmental monitor" in titles, abstracts, keywords, and *KeyWords Plus*. All information of documents was downloaded into spreadsheet software, and additional data processing was manually performed using the software Microsoft Excel. The articles that contained the searching keywords in *KeyWords Plus* only were deleted (Fu et al. 2012). Affiliations in England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK) (Chiu and Ho 2005). Affiliations in Hong Kong before 1997 were included with China (Fu et al. 2012).

Performance of publication

Outputs and language of publication

The number of articles from 1993 to 2012 and the citations per publication are presented in Fig. 1. There were 5188 publications indexed in the SCI-Expanded, which included 4605 publications of article. As the most popular document type, article comprised about four fifths of the total production and was dominant in terms of the document types. The number of environmental monitoring publications increased from 100 in 1993 to 466 in 2012. The results indicated that annual output of the related scientific articles increased steadily. The citations per publication decreased continuously from 2004 to 2012, meaning that the accumulative effect of the citation for a publication will emerge at least eight years. The largest

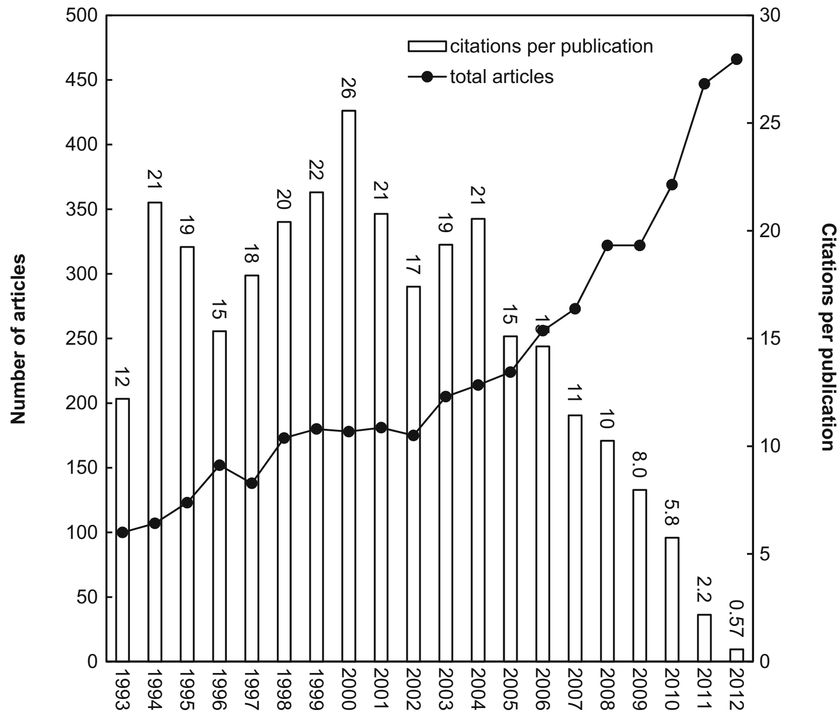


Fig. 1 The trends of annual articles and citations per publication during 1993–2012

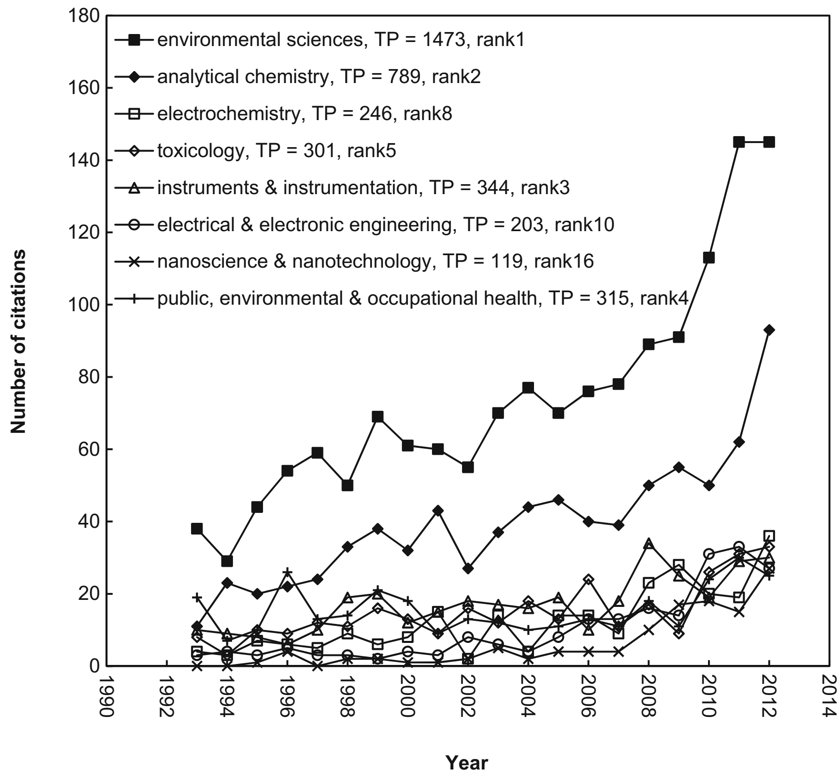
number of authors in a single article was 136, for an article published in Classical and Quantum Gravity, 2007, conducted research on the data quality for burst analysis of Virgo (Acernese et al. 2007). The average article lengths fluctuated slightly, with an overall average of 9.87 pages. The references cited per article increased throughout the 20 years. Thirteen languages were used in terms of total articles. English, as the most popular language, comprised 97% of the total articles and was followed distantly by Chinese (32 articles). The other top four languages were German, Portuguese, French, and Japanese.

Web of Science categories and journals

The category of environmental sciences contributed the most of 1473 articles, followed by analytical chemistry, instrument and instrumentation, and public and occupational health. The number of articles in environmental sciences and analytical chemistry ranked 1st and 2nd and grew quickly from 1993 to 2012 (Fig. 2). They had the highest growth rate and the most energy in recent years and were unlikely to be exceeded by other categories in the foreseeable future. According to the category description in Web of Science (http://admin-apps.webofknowledge.com/JCR/static_html/scope_notes/SCIENCE/2011/SCOPE_SCI.htm), environmental sciences covers resources concerning many aspects of the study of the environment, among them environmental contamination and toxicology, environmental health, environmental monitoring, environmental geology, and environmental management. This category also includes soil science and conservation, water resource research and engineering, and climate change. Analytical chemistry covers resources on the techniques that yield any type of information about chemical systems. Topics include chromatography, thermal analysis, chemometrics, separation techniques, pyrolysis, and electroanalytical and radioanalytical chemistry. Some spectroscopy resources may be included in this category when focusing on analytical techniques and applications in chemistry.

A total of 4605 articles were published in a wide range of 1362 journals. Among these journals, 1280 (94%) journals contained less than 10 articles. The value of the indicator *impact factor* for each journal was obtained from JCR for 2012. The *Environmental Monitoring and Assessment* published the most articles with 184 articles (impact factor 1.592), while the *Sensors and Actuators B-Chemical* ranked second with 97 articles (impact factor = 3.535), followed by the *Journal of Environmental Monitoring* (impact factor 2.085). The percentage of the top productive journal was not high, which indicates the breadth of article distribution as well as the broad interest in environmental monitoring from various research angles. This phenomenon also appears in other environment-related research areas, such as the *Atmospheric Environment* in atmospheric simulation (Li et al. 2009b) and the *Water Research* in papers concerning drinking water (Fu et al. 2013). The most widely cited article was published in the *IEEE Personal Communications* with 1012 citations, conducted research on reviewing localization techniques and evaluating the effectiveness of a very simple connectivity-metric method for localization in outdoor environments (Bulusu et al. 2000).

Fig. 2 Comparison the growth trends of top 8 subject categories



Country/territory and institution

Of 4605 articles with author addresses, 81% was single-country articles and 19% was internationally collaborative articles. The articles covered 114 different countries or territories, reflecting a great geographical diversity. According to their production, the 114 countries were divided into four parts. Particularly, 68 countries (60%) belonged to the first part of 1–10 articles; 33 countries (29%) belonged to the second part of 11–100 articles; 12 countries (11%) belonged to the third part of 101–1000 articles; and only one country (the USA) belonged to the fourth part of over 1000 articles, which totally published 1268 articles.

The top 20 countries, which ranked by the total number of articles from 1993 to 2012, are listed in Table 1 with five indicators of total number of articles, independent country articles, internationally collaborative articles, first author articles, and corresponding author articles (Malarvizhi et al. 2010). The industries of Europe and America and other developed countries developed rapidly, and the environment pollutions were getting more and more serious in 1970s. Therefore, these countries began to attach importance to environmental protection far earlier than developing countries. During the Conference on the Human Environment in 1972, there were only 11 countries that set up the national environmental management institutions, and most of them were western developed countries. Three American countries, eleven European countries, five Asian countries/territories, and one Oceania

Table 1 The 20 most productive countries/territories

Country/territory	TP	IP R (%)	CP R (%)	FP R (%)	RP R (%)
USA	1268	1 (26)	1 (35)	1 (25)	1 (24)
UK	443	2 (7.5)	2 (20)	2 (7.6)	2 (7.5)
Italy	357	3 (7.1)	6 (11)	3 (6.9)	3 (6.9)
Germany	349	5 (5.4)	3 (18)	5 (5.8)	5 (5.8)
China	333	4 (6.3)	4 (12)	4 (6.3)	4 (6.3)
Canada	251	7 (4.2)	5 (11)	6 (4.2)	6 (4.2)
Japan	213	6 (4.6)	13 (4.9)	7 (4.1)	6 (4.2)
Spain	194	8 (3.5)	8 (7.9)	8 (3.6)	8 (3.6)
Australia	175	9 (3.2)	9 (7.0)	9 (3.3)	9 (3.3)
France	153	13 (2.0)	7 (10)	12 (2.2)	12 (2.3)
Brazil	149	10 (2.9)	13 (4.9)	10 (2.8)	10 (2.8)
Sweden	140	11 (2.4)	10 (6.3)	11 (2.4)	11 (2.4)
Russia	114	12 (2.2)	18 (3.9)	13 (2.0)	13 (2.1)
South Korea	89	15 (1.7)	20 (3.1)	14 (1.7)	14 (1.7)
Netherlands	84	20 (0.91)	11 (6.2)	17 (1.1)	18 (1.1)
India	78	14 (1.8)	33 (1.2)	15 (1.6)	15 (1.6)
Taiwan	75	16 (1.7)	29 (1.6)	16 (1.5)	16 (1.5)
Belgium	73	18 (1.0)	15 (4.6)	19 (1.1)	19 (1.0)
Austria	68	26 (0.64)	12 (5.4)	23 (0.86)	23 (0.85)
Norway	66	22 (0.8)	16 (4.4)	20 (1.0)	20 (1.0)

TP total articles; IP R (%) rank and the percentage of independent articles; CP R (%) rank and the percentage of international collaborative articles; FP R (%) rank and the percentage of first author articles; RP R (%) rank and the percentage of the corresponding authored articles country, Australia, were ranked in the top 20 of publications. There were no African countries in the top 20. The seven major industrial countries (Canada, France, Germany, Italy, Japan, the UK, and the USA) were ranked in the top ten. The publications of China ranked fifth with 333 articles, which is consistent with the results of languages.

The top seven countries of more than 200 articles are shown in Fig. 3 by the number of articles from 1993 to 2012. The articles of the USA had a steady growth with tiny fluctuations throughout the 20 years. It showed the greatest counts of world publications, followed distantly by other countries. China presented a rapid growth rate from eight in 2005 to 74 in 2012, especially since the 11th Five-Year Plan in 2006 (Liu et al. 2012). As a developing country, rapid economic development and population growth in China in the last two decades had left a legacy of widespread environmental pollution (Zhu et al. 2007). The pressure to maintain high rates of growth has generally taken precedence over environmental protection. However, these issues were taken seriously by the top leadership of the Chinese government and were incorporated into policies and plans at the highest levels (Cao et al. 2009). China has set down sustainable development as a basic national strategy since 1992, and the environmental policy framework had been vigorously developed and renewed, resulting in a generally adequate set of environmental policies and regulation (Zhang and Wen 2008). The rapid development of environmental policy promoted the research in the field of environmental protection. As a technical support and decision-making subject, environmental monitoring attracted extensive attention and developed rapidly after 2000.

The top ten institutions were ranked by the number of articles (Table 2). Among the top ten institutions, six were in the USA, and one each in China, Italy, Russia, and Spain. Leading was the Environmental Protection Agency of United States (U.S. EPA) with 158 articles, which had a large disparity with the others, and almost twice that of the Chinese Academy of Sciences in China with 85 articles. The U.S. EPA also published the most independent, collaborative articles, first authored, corresponding authored articles, and cited references count articles. The U.S. EPA was established on December 2, 1970 to consolidate in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities to ensure environmental protection. Its size expanded rapidly, and the investment also increased greatly, and the research in the field of environmental protection had a very substantial lead. The result of institutions' output should be interpreted in the context of bias. The Chinese Academy of Sciences has over 100 branches in different cities. The articles of different branches are pooled under one heading, and articles divided into branches would result in different rankings (Li et al. 2009a).

Words analysis

The title and the author keywords provide a detailed description of an article's theme. Since one article certainly has title

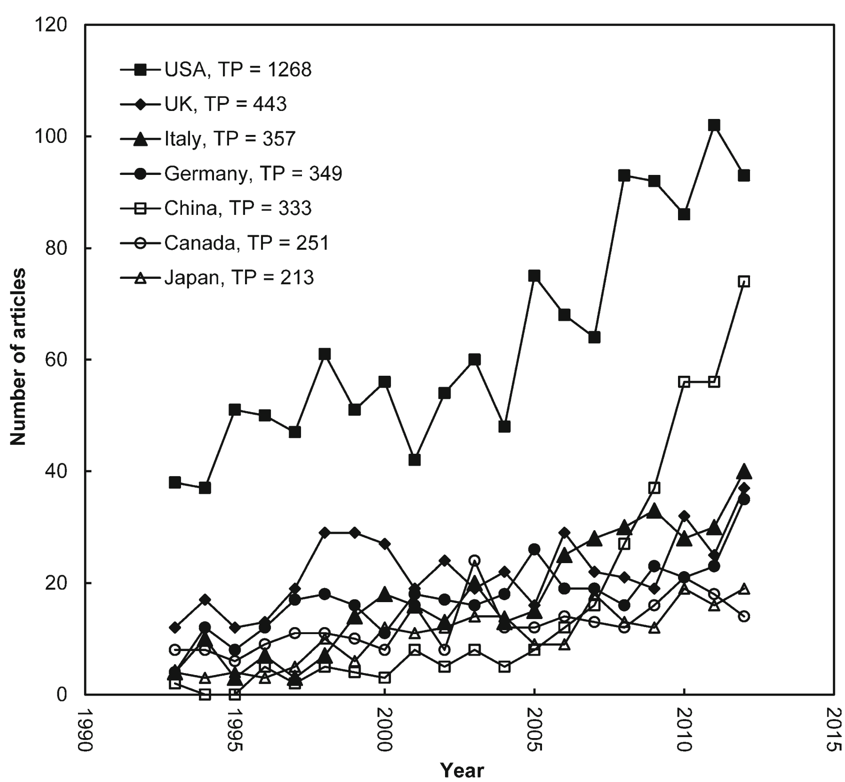


Fig. 3 Comparison the growth trends of the top 7 countries

Table 2 The 10 most productive institutions

Institute	TP	IP R (%)	CP R (%)	FP R (%)	RP R (%)	NP R (%)
U.S. Environmental Protection Agency, USA	158	1 (3.1)	1 (3.9)	1 (2.2)	1 (2.3)	1 (5.1)
Chinese Academy of Sciences, China	85	2 (1.6)	2 (2.1)	2 (1.3)	2 (1.3)	3 (1.8)
Oregon State University, USA	51	9 (0.5)	3 (1.7)	5 (0.53)	5 (0.51)	2 (2.2)
National Research Council, Italy	44	5 (0.59)	4 (1.3)	3 (0.66)	3 (0.67)	5 (1.4)
Russian Academy of Sciences, Russia	36	3 (1.1)	21 (0.55)	4 (0.59)	4 (0.6)	120 (0.26)
National Oceanic and Atmospheric Administration, USA	34	19 (0.32)	5 (1.1)	10 (0.42)	10 (0.4)	4 (1.4)
Spanish National Research Council (CSIC), Spain	34	13 (0.46)	7 (1.0)	8 (0.46)	8 (0.45)	9 (0.84)
University of California, USA	32	27 (0.27)	6 (1.1)	13 (0.37)	13 (0.36)	6 (1.2)
University of California (Davis), USA	32	5 (0.59)	8 (0.8)	8 (0.46)	9 (0.42)	23 (0.58)
University of Washington, USA	29	9 (0.5)	10 (0.76)	7 (0.48)	7 (0.49)	10 (0.77)

TP total articles; IP R (%) rank and the percentage of independent articles; CP R (%) rank and the percentage of international collaborative articles; FP R (%) rank and the percentage of first author articles; RP R (%) rank and the percentage of the corresponding authored articles; NP R (%) rank and the percentage of cited references count

but do not always has author keywords and *KeyWords Plus*, the sample size of title was the greatest. However, the meaning of the single words in title sometimes does not make sense, in need of referring to the author keywords and *KeyWords Plus* for well-understanding. The synthesized analysis of words in title, author keywords, and *KeyWords Plus* has proved to be a helpful method in revealing the research hotspots and discovering scientific research trends in recent years (Chiu and Ho 2007; Xie et al. 2008; Li et al. 2009b). Among 4605 articles, 3255 articles (80%) had records information of author keywords, while 3577 articles (88%) with *KeyWords Plus* information were analyzed. Tables 3, 4 and 5 listed the most frequently used words in title, author keywords, and *KeyWords Plus*.

In terms of author keywords, the contaminant of "heavy metals" attracted much attention in environmental monitoring research and ranked 4th in author keywords list. Similarly, heavy metals ranked 16th in *KeyWords Plus* list. Heavy metals have been used by humans for thousands of years, and the

Table 3 The 20 most frequently used title words during 1993–2012

Title words	TP	93-12 R (%)	93-97 R (%)	98-02 R (%)	03-07 R (%)	08-12 R (%)
Monitoring	1227	1 (27)	1 (35)	2 (28)	1 (28)	1 (23)
Environmental	1226	2 (27)	2 (35)	1 (30)	2 (27)	2 (22)
Detection	294	3 (6.4)	3 (6.1)	3 (5.6)	4 (5.8)	4 (7.2)
Sensor	268	4 (5.8)	44 (1.3)	9 (3.9)	6 (4.7)	3 (8.8)
Water	237	5 (5.1)	10 (2.6)	8 (4.6)	3 (7.1)	5 (5)
System	215	6 (4.7)	6 (4.4)	5 (4.8)	7 (4.3)	6 (4.9)
Assessment	215	6 (4.7)	5 (4.8)	4 (5.2)	5 (4.9)	8 (4.2)
Exposure	162	8 (3.5)	4 (5.2)	5 (4.8)	9 (3.4)	19 (2.4)
Determination	143	9 (3.1)	15 (2.3)	7 (4.7)	10 (3.2)	17 (2.5)
Development	134	10 (2.9)	21 (1.9)	16 (2.7)	8 (3.8)	13 (2.8)
Quality	130	11 (2.8)	15 (2.3)	11 (3)	12 (2.9)	12 (2.9)
Sensing	128	12 (2.8)	55 (1.1)	13 (2.9)	19 (2.3)	10 (3.5)
Evaluation	127	13 (2.8)	19 (2.1)	13 (2.9)	11 (3.1)	14 (2.7)
Networks	125	14 (2.7)	335 (0.32)	293 (0.45)	12 (2.9)	7 (4.4)
Effects	118	15 (2.6)	38 (1.5)	11 (3)	12 (2.9)	18 (2.5)
Air	109	16 (2.4)	24 (1.8)	24 (2)	26 (2)	11 (2.9)
Gas	109	16 (2.4)	15 (2.3)	19 (2.6)	18 (2.4)	22 (2.3)
Chemical	107	18 (2.3)	8 (2.7)	16 (2.7)	36 (1.8)	21 (2.3)
Sensors	107	18 (2.3)	13 (2.4)	10 (3.3)	49 (1.6)	22 (2.3)
Soil	100	20 (2.2)	24 (1.8)	15 (2.8)	33 (1.9)	25 (2.2)

Table 4 The 20 most frequently used author keywords during 1993–2012

Author keywords	TP	93-12 R (%)	93-97 R (%)	98-02 R (%)	03-07 R (%)	08-12 R (%)
Environmental monitoring	999	1 (31)	1 (31)	1 (38)	1 (30)	1 (28)
Monitoring	109	2 (3.3)	2 (6.5)	2 (4.1)	2 (3.1)	2 (2.6)
Remote sensing	65	3 (2)	8 (2.1)	15 (1)	3 (2.2)	3 (2.3)
Heavy metals	65	3 (2)	4 (2.4)	3 (2.9)	6 (1.6)	4 (1.8)
Biosensor	49	5 (1.5)	16 (1.4)	5 (2.2)	11 (1.3)	7 (1.4)
Water quality	48	6 (1.5)	4 (2.4)	10 (1.4)	5 (1.9)	12 (1.1)
Pesticides	41	7 (1.3)	12 (1.7)	4 (2.6)	13 (1.1)	25 (0.73)
Biomarkers	38	8 (1.2)	4 (2.4)	7 (1.5)	39 (0.57)	9 (1.1)
GIS	36	9 (1.1)	50 (0.68)	59 (0.51)	6 (1.6)	9 (1.1)
Environment	35	10 (1.1)	16 (1.4)	7 (1.5)	17 (1)	18 (0.86)
Pollution	35	10 (1.1)	12 (1.7)	15 (1)	4 (2.1)	57 (0.4)
Biomonitoring	35	10 (1.1)	16 (1.4)	10 (1.4)	23 (0.8)	12 (1.1)
Biological monitoring	34	13 (1)	3 (2.7)	13 (1.2)	13 (1.1)	31 (0.6)
Soil	32	14 (1)	12 (1.7)	24 (0.86)	20 (0.92)	17 (0.93)
Risk assessment	31	15 (1)	16 (1.4)	59 (0.51)	9 (1.5)	25 (0.73)
Biomarker	31	15 (1)	50 (0.68)	109 (0.34)	10 (1.4)	15 (1)
Air pollution	29	17 (0.89)	16 (1.4)	59 (0.51)	23 (0.8)	15 (1)
Genotoxicity	29	17 (0.89)	16 (1.4)	6 (1.9)	13 (1.1)	115 (0.27)
Wireless sensor networks	28	19 (0.86)	N/A	N/A	32 (0.69)	5 (1.5)
Metals	27	20 (0.83)	16 (1.4)	15 (1)	23 (0.8)	27 (0.66)
Fish	27	20 (0.83)	16 (1.4)	32 (0.68)	23 (0.8)	20 (0.8)

emissions and hazards of heavy metal contamination were of wide concern. As one kind of popular heavy metal contaminants, the "cadmium" ranked 12th in *KeyWords Plus* list, and a UNEP/WHO project on the assessment of human

Table 5 The 20 most frequently used *KeyWords Plus* during 1993–2012

KeyWords Plus	TP	93-12 R (%)	93-97 R (%)	98-02 R (%)	03-07 R (%)	08-12 R (%)
Water	169	1 (4.7)	1 (8.6)	1 (3.8)	1 (4.4)	1 (4.5)
System	123	2 (3.4)	10 (1.8)	2 (3.3)	2 (3.9)	2 (3.6)
Exposure	114	3 (3.2)	3 (2.7)	3 (3)	3 (3.2)	3 (3.4)
Pollution	102	4 (2.9)	2 (4.1)	11 (2)	5 (3.1)	4 (2.8)
Samples	78	5 (2.2)	17 (1.5)	3 (3)	6 (2.5)	14 (1.8)
Management	76	6 (2.1)	35 (1.2)	8 (2.3)	27 (1.5)	6 (2.6)
Identification	74	7 (2.1)	5 (2.1)	25 (1.3)	17 (1.7)	6 (2.6)
Toxicity	73	8 (2)	17 (1.5)	17 (1.4)	3 (3.2)	17 (1.8)
Model	71	9 (2)	5 (2.1)	25 (1.3)	12 (2)	9 (2.2)
Contamination	71	9 (2)	35 (1.2)	25 (1.3)	13 (1.9)	8 (2.5)
Fish	69	11 (1.9)	5 (2.1)	11 (2)	9 (2.1)	17 (1.8)
Cadmium	67	12 (1.9)	17 (1.5)	5 (2.7)	7 (2.3)	28 (1.4)
Design	64	13 (1.8)	4 (2.4)	100 (0.63)	73 (0.85)	5 (2.7)
Sediments	63	14 (1.8)	10 (1.8)	5 (2.7)	15 (1.8)	28 (1.4)
Sensors	62	15 (1.7)	93 (0.59)	17 (1.4)	17 (1.7)	10 (2.1)
Heavy-metals	62	15 (1.7)	93 (0.59)	25 (1.3)	13 (1.9)	12 (2.1)
Soil	60	17 (1.7)	5 (2.1)	8 (2.3)	17 (1.7)	32 (1.3)
Classification	59	18 (1.6)	93 (0.59)	64 (0.78)	7 (2.3)	14 (1.8)
Sensor	59	18 (1.6)	17 (1.5)	15 (1.7)	39 (1.2)	13 (1.9)
Spectroscopy	58	20 (1.6)	17 (1.5)	36 (1.1)	17 (1.7)	14 (1.8)

exposure to cadmium through analysis of blood and kidneys was carried out (Friberg and Vahter 1983). The pesticides, another primary contaminant in environmental monitoring research, also attracted much attention, and it ranked 7th in author keywords. The research about environmental monitoring and ecological risk assessment for pesticide contamination and effects were carried out in Lake Pamvotis, northwestern Greece (Hela et al. 2005). Analytical methods for the analysis of pesticides were also widely discussed (DiCorcia and Marchetti 1992; Chiron et al. 1993).

Researchers paid more attention on water environment monitoring than other environmental factors in the last 20 years. Water was the most frequently used word in *KeyWords Plus* list, which also ranked 5th in title words. Similarly, "water quality" ranked 6th in author keywords list. Soil and air, by contrast, were present at lower frequencies. "Soil" ranked 20th in title words, 14th in author keywords, and 17th in *KeyWords Plus* list. "Air" ranked 16th in title words and not even make the top 20 in *KeyWords Plus* list, and "Air pollution" ranked 17th in author keywords.

Numerous environmental monitoring methods and devices have been studied. Other than the searching keyword "environmental monitoring", the most frequent author keyword was "remote sensing." With respect to title words, much concern was attracted on "detection" and "sensor." As a special kind of sensor, biosensor played an important role in the field of environmental monitoring devices, and it ranked 5th in author keywords. The unprecedented interest in the development and exploitation of analytical devices for detection, quantification, and monitoring of specific chemical species has led to the emergence of biosensors. Biosensor instruments are specific, rapid, simple to operate, and can be easily fabricated with minimal sample pretreatment involved. The apparently alien marriage of two contrasting disciplines combines the specificity and sensitivity of biological systems with the computing power of microprocessor (Borole et al. 2006). Because of their exceptional performance capabilities, which include high specificity and sensitivity, rapid response, low cost, relatively compact size, and user-friendly operation, biosensors have become an important tool for detection of chemical and biological components for environmental monitoring (Amine et al. 2006).

Hot issues

Word cluster analysis method can represent the possible research hotspots of this field. It was a continuation of the three keywords (word in title, author keyword, and keyword plus) analysis. Each word cluster was composed of several supporting words, by analyzing the number of publications containing these "word clusters," and the overview of the research hotspots could be revealed (Mao et al. 2010). The possible research hotspots of contaminants and monitoring methods, two main aspects in environmental monitoring research, were summed up.

The possible research hotspots of contaminants of environmental monitoring research were "organic contaminants" (organic pollutants, organic chemicals, organic-chemicals, organic-matter, organic-compounds, polycyclic aromatic hydrocarbons, polycyclic aromatic-hydrocarbons, aromatic-hydrocarbons, volatile organic compounds, volatile organic-compounds, VOCs, VOC, benzene, PCBs, polychlorinated biphenyls, polychlorinated-biphenyls, polychlorinated biphenyl congeners, PCB, PAHs, PAH, toluene, dioxin, dioxins, phenols, hydrocarbons, persistent organic pollutants, POPs, organotin, organophosphates, organophosphate, cyclophosphamide, polyaniline, methane, formaldehyde, styrene, methylmercury, ifosfamide, 2,4-dichlorophenoxyacetic acid, 2,4-d, brominated flame retardants, organic-solvents, surfactants, bisphenol-a, benzo[a]pyrene, cortisol, triazine herbicides, 2,4,6-trinitrotoluene, TNT, polybrominated diphenyl ethers, pcdds, pcdfs, vinyl-chloride, chlorinated hydrocarbons, PBDEs, pesticides, pesticide, atrazine, carbaryl, herbicides, organochlorine, organochlorines, organochlorine pesticides, carbamate pesticides, organochlorine contaminants, ddt, pyrethroid, insecticides, terbuthylazine, permethrin, propanil, chlorpyrifos, glyphosate, s-triazine herbicides), "heavy metal" (heavy metals, heavy-metals, heavy metal, heavy-metal, heavy metal ions, heavy-metal ions, bioavailable heavy-metals, antimony, lead, Pb, Pb(II), mercury, cadmium, Cd(II), chromium, copper, arsenic, zinc, Zn, platinum, nickel, cobalt, Co, lr), and "radiation" (uranium, radionuclides, radionuclide, long-lived radionuclides, radon, cs-137, radioxenon, xenon, Xe-133, plutonium, Rn-222, actinides, Sr-90, Po-210, Kr-85, Ra-226, c-14, u-236).

The article number growth trends of three contaminants are compared in Fig. 4. Studies on "organic contaminants" rose rapidly and have taken the lead in recent years. It held 1009 articles in all and 100 articles in 2011.The usefulness of DDT as an insecticide had been widely discussed in 1940s (Annand 1944; Bodenstein 1946). Also, the detection of DDT by colorimetric tests was reported in 1944 (Schechter and Haller 1944). Since the publication of Silent Spring in the 1960s, much attention has been paid to the environmental pollution and hazards to human health introduced by the wide agricultural usage of organochlorine pesticides. The relation between polychlorinated biphenyls (PCB) in the global ecosystem and the aberration of calcium metabolism in birds was examined in 1968 (Risebrough et al. 1968). The pollutant of insecticides (Applegat 1970), pesticide residues of malathion (Guerrant et al. 1970), and DDT (Ware et al. 1970) were reported in 1970s. After public concerns about the health effects of the widely used pesticide DDT, the U.S. EPA bans its use and requires extensive review of all pesticides in 1972 (USEPA 1972). As time goes on, there were more and more actions and international conventions to control organic pollutants.

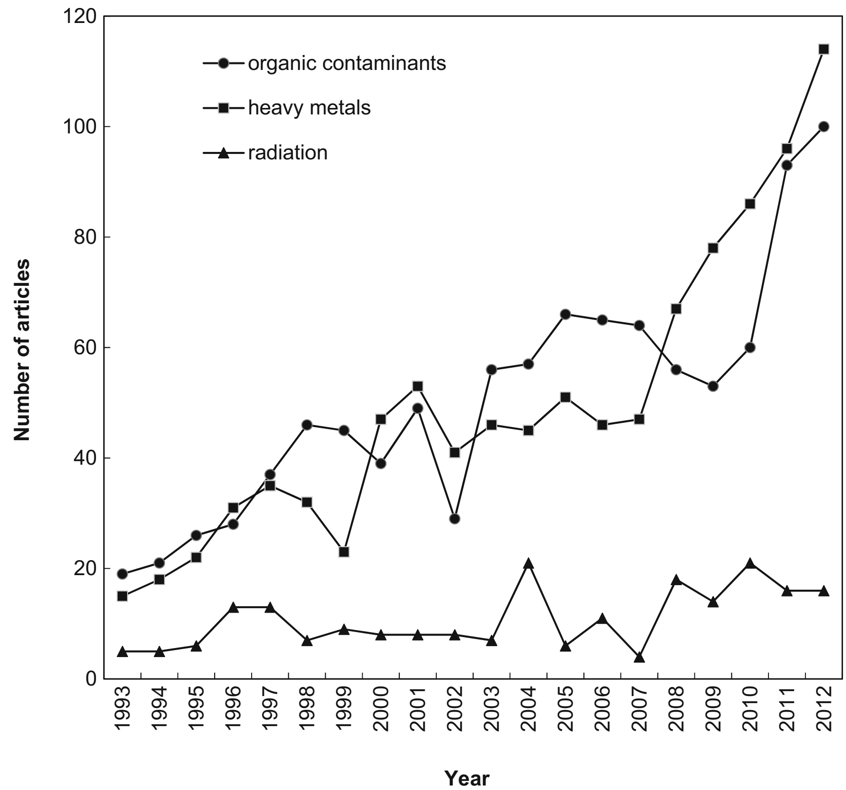


Fig. 4 Growth trends of three contaminants during 1993–2012

According to the toxicity of organic pollutants, the possibility of biodegradation and the probability of occurrence in the water body, the United States Environmental Protection Agency (U.S. EPA) selected 129 priority control pollutants in 1977, and of these, 114 were organic compounds (21 kinds of pesticides, 26 kinds of halogenated hydrocarbon fat, 8 kinds of PCBS, 11 kinds of phenol, 7 kinds of nitrite and other compounds), accounting for 88.4% of the total (USEPA 1977). The European Union (EU), the World Health Organization (WHO), Japan, and China also have established their own list of priority control organic pollutants. The Rotterdam Convention established international legal obligations on its parties that prior informed consent would be sought before certain hazardous chemicals or pesticides were internationally traded (UNEP and FAO 1998). The Stockholm Convention on persistent organic pollutants (POPs) identified 12 chlorinated chemical groups (8 individual OCPs, HCB, PCBs, and PCDD/Fs) for global bans or reduced emissions (UNEP 2001).

The 2nd position "heavy metal" followed the same trend as the "organic contaminants." The number of articles with heavy metal showed a sharp rise with the highest growth rate from 15 in 1993 to 114 in 2012, and 993 articles were published during 1993–2012. Heavy metal contamination is of serious concern to human health since these substances are non-biodegradable and retained by the ecological system (Verma and Singh 2005). The main threats to human health from heavy metals are associated with exposure to lead, cadmium, mercury, and arsenic (Chisolm 1980; MacIntosh et al. 1996; Jarup 2003). Minamata disease was a breakout in Minamata Bay, Kumamoto Prefecture, Japan, between 1953 and 1956 (Eto 1997). Researches showed that the disease was caused by human ingestion of a large amount of methylmercury-contaminated fish or shellfish, and the mercury came from a nearby chemical plant (Chisso Co. Ltd.) (Harada 1995). Minamata drew the world's attention to the devastating effects of mercury, and an international convention to control mercury emissions was signed in 2013. Named the Minamata Convention on Mercury, the agreement was a response to the realization that mercury pollution is a global problem that no one country can solve alone, and more than 130 nations agreed by consensus to a final text (Kessler 2013). The Minamata Convention on Mercury is a global treaty to protect human health and the environment from the adverse effects of mercury (UNEP 2013). The most frequently used testing method of heavy metal ions includes atomic absorption spectrometry and inductively coupled plasma mass spectrometry. Fluorescent and colorimetric sensors for detection of lead, cadmium, and mercury ions attracted much attention (Kim et al. 2012). The hazards and the monitoring methods of heavy metal contamination have been extensively studied in soils (Brookes 1995; Facchinelli et al. 2001), sediments (Forstner 1976; Liu et al. 2003), fish (Rashed 2001), and sewage sludge (Scancar et al. 2000). Heavy metals health risk assessment for population through vegetables (Harmanescu et al. 2011), food crops and fruits (Orisakwe et al. 2012), and drinking water (Khan et al. 2016) consumption was discussed in recent years.

The "radiation" had a large disparity with the above two kinds of pollutants, and the number of articles with radiation had no obvious change in 20 years. Since the commercial development of nuclear power in 1950s, it is required to regulate the anticipated nuclear industry to protect public health and safety from radiation hazards (Keller and Modarres 2005). The IAEA Statute was entered into force in 1957, and the first session of the IAEA General Conference took place of the same year. In order to promote the safe, secure, and peaceful use of nuclear technologies, the Convention on the Physical Protection of Nuclear Material was signed on 3 March 1980. The Convention is the only international legally binding undertaking in the area of physical protection of nuclear material. It establishes measures related to the prevention, detection, and punishment of offenses relating to nuclear material (IAEA 1980). Five months after the Chernobyl nuclear accident, the Convention on Early Notification of a Nuclear Accident was adopted in September 1986. The Convention need for states to provide relevant information about nuclear accidents as early as possible, in order that transboundary radiological consequences can be minimized (IAEA 1986). The main reason for the low degree of concern is that the probability and frequency of the radiation contamination were low due to the strict usage and management, which led to the low number of relative researches and articles.

The possible research hotspots of environmental monitoring methods were "remote sensing" (remote sensor, remote-sensing, remotely sensed, remote monitoring, satellite remote sensing, airborne remote sensing, thermal remote sensing, near remote sensing, low altitude remote sensing, optical remote sensing, hyperspectral remote sensing, remote-sensing techniques), "GIS" (GIS, GIS-system, webgis, web-based GIS, global information system (GIS), geographic information systems (GIS), arcgis, mobile GIS), and "wireless sensor networks" (wireless sensor networks (WSNS), wireless sensor network, wireless sensor network (WSN), WSN, wireless networks, wireless sensors network). The development of the monitoring methods was identified in Fig. 5.

Remote sensing was a technology based on aerial photography in the early 1960s. Airborne remote sensing was the main technology at the early stage; then, the United States launched the first land satellite, which marked the beginning of the era of space remote sensing in 1972. Various types of land satellite had been launched since the 1980s, and they provided rich data for the research fields of environment, meteorology, geology, and so on (Ma et al. 2012) The remote sensing was widely used in air quality and water quality, for instance, the AERONET—a federated instrument network and data archive for aerosol characterization (Holben et al. 1998), estimating ground-level $PM_{2.5}$ in the eastern United States (Liu et al. 2005), a semi-operative approach to retrieve chlorophyll-a concentration from airborne spaceborne

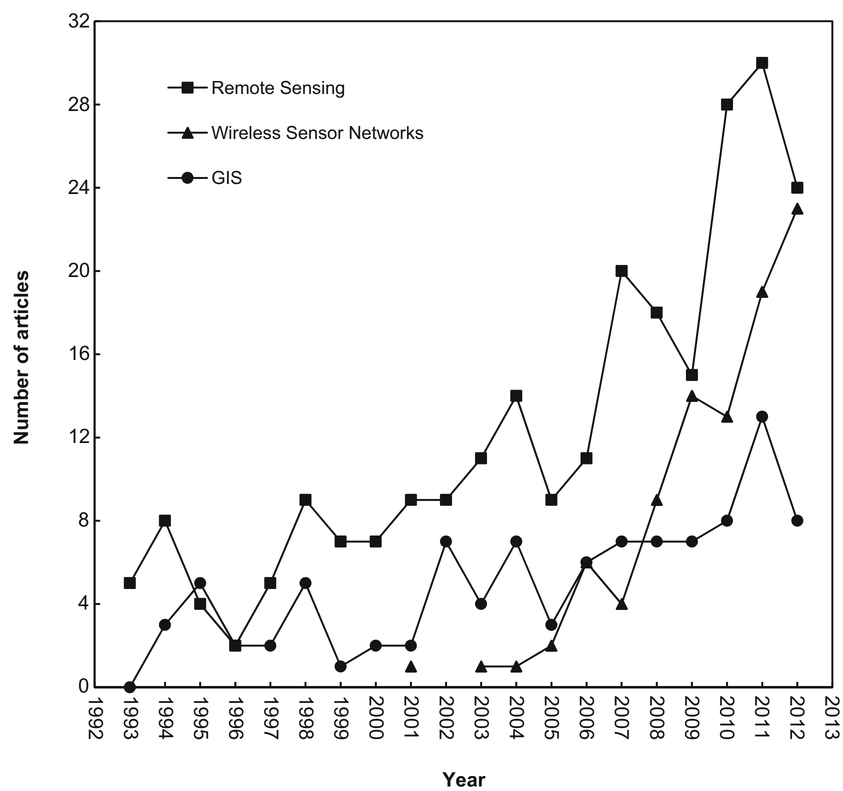


Fig. 5 Growth trends of monitoring methods during 1993–2012

spectrometer observations (Pulliainen et al. 2001), application of satellite remote sensing combined with a water quality model and in situ data for total suspended matter (TSM) in the southern Frisian lakes (Dekker et al. 2001), and the suitability of the airborne imaging spectrometer for monitoring lake water quality (Kallio et al. 2001) of 11 lakes located in southern Finland. Remote sensing from airborne and spaceborne platforms provides valuable data for environmental monitoring, and a multi-resolution, object-oriented fuzzy analysis approach was discussed, which provides an appropriate link between remote sensing imagery and GIS (Benz et al. 2004). Remote sensing imagery needs to be converted into tangible information which can be utilized in conjunction with other data sets, often within widely used Geographic Information Systems (GIS) (Blaschke 2010).The geographical information system (GIS) has been specifically used in soil pollution maps of heavy metals (Facchinelli et al. 2001), "total" metals (Li et al. 2004), and trace metals (Lee et al. 2006), as well as spatial distribution and hazard assessment of lead in soil (McGrath et al. 2004).

It is noticeable that no article with wireless sensor network had been published until 2001, but the number of articles showed a sharp rise with the highest growth rate from 1 in 2001 to 23 in 2012. Data collection networks are keys to environmental problem recognition, diagnosis, and solution development (Wedderburn 1998). Wireless sensor networks (WSN) consist of small nodes with sensing, computation, and wireless communications capabilities (Al-Karaki and Kamal 2004). A wireless sensor network (WSN) has important applications such as remote environmental monitoring and target tracking in recent years (Yick et al. 2008). The wireless sensor networks have been widely applied in environmental monitoring as environmental sensor networks, which have evolved from passive logging systems into intelligent sensor networks that comprise a network of automatic sensor nodes and communications systems, and actively communicate their data to a sensor network server (Hart and Martinez 2006). The techniques of sensor networks attached much attention in 2000s, for example, localization techniques (Bulusu et al. 2000), and medium access control protocol designed (Ye et al. 2004).

Conclusions

An overview of research in the environmental monitoring field was presented with the information of related outputs, language, categories, journals, countries, institutions, words, and hot issues. The annual output of environmental monitoring publications increased steadily during 1993–2012. English was the most popular language over all the articles. The category of environmental sciences and analytical chemistry had the highest growth rate and unlikely to be exceeded by other categories in the foreseeable future. The *Environmental Monitoring and Assessment* published the most articles with a low percentage reflecting the broad interest in environmental monitoring from various research angles. The USA and the UK had high productivity in all five indicators. The U.S. Environmental Protection Agency took the leading position of the institutions in total publications. The synthesized analysis by words in title, author keywords, and *KeyWords Plus* provided the clues for hot issues. Researchers paid more attention on water environment monitoring than other environmental factors in the last 20 years. The contaminants including organic contaminants, heavy metal, and radiation are the most common research focuses, and the organic contaminants and heavy metal of the degree of concern are gradually rising. Numerous environmental devices and monitoring methods have been widely studied. Sensor and biosensor played an important role in the field of environmental monitoring devices. In addition to conventional device detection method, the remote sensing, GIS, and wireless sensor networks were the mainstream environmental monitoring methods. In addition to the above, the continuous efforts of international organization, social awareness, and the various countries' positive and effective political and environmental policies promoted the research and published articles in the field of environmental monitoring.

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