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A bibliometric analysis of world volatile organic compounds research trends

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Abstract This study explores a bibliometric approach to quantitatively assessing current research trends on volatile organic compounds, by using the related literature in the Science Citation Index (SCI) database from 1992 to 2007. The articles acquired from such literature were concentrated on the general analysis by scientific output, the research performances by countries, institutes, and collaborations, and the research trends by the frequency of author keywords, words in title, words in abstract, and keywords plus. Over the past years, there had been a notable growth trend in publication outputs, along with more participation and collaboration of countries and institutes. Research collaborative papers had shifted from the national inter-institutional to the international collaboration. Benzene, toluene, and formaldehyde were the three kinds of VOCs concerned mostly. Detection and removing, especially by adsorption and oxidation, of VOCs were to be the orientation of all VOCs research in the next few years.

Keywords Volatile organic compounds · Research trend · Scientometrics · SCI

Introduction

Volatile organic compounds (VOCs) research is one of the most important areas in chemical and environmental sciences today. Scientific articles on VOCs research have

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demonstrated an expeditious increase in quantity over the past several decades, and a number of papers presenting the latest research achievements have been published in the authoritative scientific journals such as Nature and Science (Simonich and Hites 1994; Lewis et al. 2000; Di Carlo et al. 2004; Lund and Bohlmann 2006). VOCs research has obtained increasing scientific attention mainly due to their negative effects on human health and environmental deterioration. Firstly, VOCs are ubiquitous and numerous in the environment, workplace, and consumer products (Brown et al. 1994; Wolkoff and Nielsen 2001). Among the 189 chemicals which have been identified as hazardous air pollutants by Clean Air Act Amendments, nearly 100 of them are VOCs (MacKenzie et al. 1991). Therefore, humans can be easily exposed to VOCs through skin contact, breathing, and eating. Secondly, VOCs are suspected to have the primary and secondary harmful effects due to prolonged exposure (Wallace et al. 1989). High concentrations of VOCs are known to have caused a number of health problems, including the eye and throat irritation, the headaches, and the damage to the liver and nervous system. There are indications that VOCs may be a cause of the sick building syndrome (Ten et al. 1988). In addition, some VOCs like styrene are suspected to be the hormone disruptors, for they can interfere with the normal functioning of the hormone system of both people and wildlife in a number of ways to produce a wide range of adverse effects including reproductive, developmental, and behavioural problems (Japan Environment Agency 1998). Thirdly, by reacting with other atmospheric chemicals such as nitrogen oxides (Das et al. 2004), VOCs can form photochemical smog, which contains ozone and other toxic byproducts.

Despite of high growth rate of VOCs papers, there have been few attempts at gathering systematic data on the global scientific production of VOCs research. Garfield indicated that a recent research focus could be reflected on its publication output (Garfield 1970). A common research tool is based on bibliometric methods which have already been widely applied for the scientific production and research trends in many disciplines of science and engineering (Zitt and Bassecoulard 1994; Hsieh et al. 2004; Keiser and Utzinger 2005; Zhou et al. 2007). Furthermore, the Science Citation Index (SCI) from the Web of Science databases of the Institute for Scientific Information (ISI) are the most important and frequently used source database of choice for a broad review of scientific accomplishment in all studying fields (Bayer and Folger 1966; Braun et al. 2000). Conventional bibliometric methods often evaluate the research trend by the publication outputs of countries, institutes, journals, and research fields (Braun et al. 1995; Colman et al. 1995; Ugolini et al. 1997) or by the citation analysis (Cole 1989). However, merely depending on the change in the citations or publication counts of countries and organizations cannot completely indicate the development trend or future orientation of the research field. More information, closer to the research itself, such as author keywords, words in title, and keywords plus should be introduced into the assessment of research trends (Li et al. 2008).

In this study, we aim at synthetically using both the traditional method: country, institute, subject category and journal analysis, and an innovative method: author keyword, source title, abstract, and keyword plus analysis, mapping the trends of global VOCs research during the period of 1992–2007, which would help researchers to realize the panorama of global VOCs research, and establish the further research direction.

Data sources and methodology

The data used in this study were based on the online database of the Science Citation Index (SCI) retrieved from the ISI Web of Science, Philadelphia, PA, USA. “Volatile organic compounds," "volatile organic compound", VOCs, and VOC were used as the keywords to search titles, abstracts, and keywords from 1992 to 2007. Document information included author(s), title, source, abstract, language, document type, keywords, addresses, cited reference count, times cited, publisher information, ISSN, page count, subject category, and citation report. The records were then downloaded to a compact disc. Care has been exercised to examine the data collected to assure their identity. Subsequently, the data were analyzed by Microsoft Excel. Articles originating from England, Scotland, Northern Ireland, and Wales were grouped under the UK heading. The impact factor (IF) of a journal was determined for each document as reported in the JCR 2007. Collaboration type was determined by the addresses of the authors, where "independent" was assigned if no collaboration was presented. "International collaboration" was assigned if the paper was cosigned by researchers from more than one country.

All the articles referring to VOCs during the past 16 years were assessed from the following aspects: language of publications; growth trend of publication outputs; publication performance including countries, institutes, and collaborations; publication patterns including distribution of outputs in subject categories and journals; and research emphasis including the analysis of author keyword, keyword plus, and word in title and abstract.

Results and discussion

There were totally 11,048 publications which met the selection criteria mentioned, containing 12 document types. The article was the most-frequently used document type comprising 90% of the total production, followed distantly by reviews (596; 5.4%). Others showing less significance were meeting abstracts (235; 2.1%), editorial materials (105; 1.0%), news items (87; 0.79%), letters (45; 0.41%), notes (25; 0.23%), corrections (18; 0.16%), reprints (12; 0.11%), addition corrections (5; 0.045%), discussions (2; 0.018%), and software review (1; 0.0091%). As journal articles represented the majority of document types that were also peer-reviewed within this field, 9,917 original articles were identified and further analyzed in the following study, while all others were discarded.

Language of publication

Languages of all articles in this study were grouped. As one might expect, English is the predominant language of articles on VOCs, accounting for 98% of all article publications. This may be due to the fact that the UK and the USA are the predominant countries of publication and the SCI is an American-based database. Moreover, English is the official language for most international conferences. However, as VOCs-related research had generated more and more worldwide interest (Guenther et al. 1995; Jenkin et al. 1997), an increasing share of articles in languages other than English appeared. Totally 16 languages were found in the non-English SCI publishing world for the 16 years. Similar phenomena were found in other scientific fields that were getting mature gradually (Self et al. 1989; Navarro 1996). The top three languages with respect to non-English articles were German (68; 0.69%), Chinese (51; 0.51%), and Japanese (32; 0.32%). The remaining included French (27; 0.27%), Spanish (16; 0.16%), Polish (13; 0.13%), Czech (10; 0.10%), Portuguese (9; 0.091%), Hungarian (5; 0.050%), Rumanian (2; 0.020%), Russian (2; 0.020%), Slovak (1; 0.010%), Croatian (1; 0.010%), Italian (1; 0.010%), Korean (1; 0.010%), and Lithuanian (1; 0.010%).

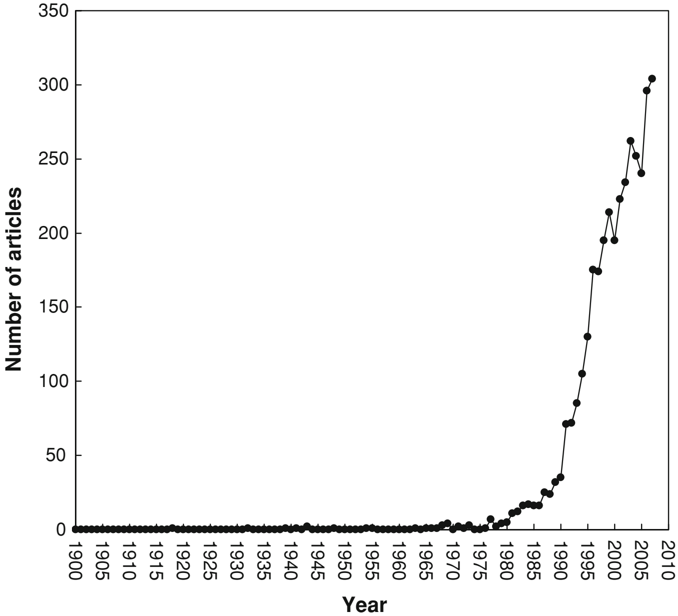

Fig. 1 World SCI publications on VOCs, 1900–2007

Publication outputs

The VOCs research developed expeditiously over the last century, from 1 article in 1918 to 304 articles in 2007 by using "volatile organic compounds," "volatile organic compound", VOCs, and VOC to search title words only (Fig. 1). The world academic publication had a notable growth after the 1980s. The publication output of current VOCs research during the time span from 1992 to 2007 was summarized in Table 1. The annual number of articles, journals, as well as countries and institutes publishing VOCs-related literature all increased considerably, indicating that the research had aroused more and more concern all over the world.

Publication performances: countries, institutes, and collaborations

The contribution of different countries/territories was estimated by the location of the affiliation of at least one author of the published papers. There were 107 articles without any author address information on the ISI Web of Science. The remaining 9,810 articles were published by 95 countries/territories. Table 2 presents the top 50 productive countries/territories during the past 16 years. The table is ranked by the number of articles that each country produced. Twenty-six European countries, twelve Asian countries/territories, four South American countries, three North American countries, three African countries and two Oceanian countries entered the ranks. It can be seen clearly that the largest contributor, USA, published 3,690 (38%) articles in total, including 2,971 independent publications and 719 international collaborative ones. Germany and the UK ranked the second and the third with 797 (8.1%) and 639 (6.5%) articles, respectively. Of all the top

Table 1 Characteristics of VOCs scientific articles, 1992–2007

Year	Article	Language	Country	Institute	Subject category	Journal
1992	168	5	23	166	53	80
1993	202	3	23	204	47	88
1994	265	3	32	266	64	117
1995	340	5	29	342	76	146
1996	405	6	35	384	73	175
1997	462	7	41	454	84	194
1998	535	8	47	533	83	220
1999	576	6	48	584	84	218
2000	586	9	47	613	81	229
2001	714	8	55	767	96	253
2002	717	7	49	802	83	259
2003	844	10	60	913	102	298
2004	909	7	58	992	108	322
2005	989	9	55	1,058	104	368
2006	1,030	8	57	1,128	108	384
2007	1,175	11	67	1,311	107	424

50 countries, Venezuela has the highest international collaborative rate (100%), followed by Chile (86%), and Estonia (85%).

There are totally 4,936 institutes taking part in the VOCs research. Table 3 provides a list of the top 20 most productive institutes between 1992 and 2007. Ten of these twenty institutes were located in USA while each of the remaining was in other countries. Obviously, USA possesses a stronger research power in VOCs field. The US Environmental Protection Agency (EPA) is the largest contributor publishing 307 papers on the subject, including 83 independent publications and 224 international collaborative ones. The National Center for Atmospheric Research (NCAR) and the University of Colorado in USA, the Chinese Academy of Sciences in China, and the University of California Berkeley in the USA, ranked second to fifth, contributing 161, 138, 111, and 109 articles, respectively. A bias would appear because the Chinese Academy of Sciences has branches in different cities. In the present study, the publications of the institutes were pooled less than one heading; therefore, dividing the publications among the branches would have given different rankings. Except for University of Waterloo in Canada and University of California Riverside in USA, all other 18 institutes in the top 20 have more collaborative publications than independent ones. As 96% of the total publications were collaborative works with other institutes, National Oceanic and Atmospheric Administration (NOAA) in USA held the highest collaboration rate. Innsbruck University in Austria and National Center for Atmospheric Research (NCAR) in USA ranked second and third, with a rate of 94% and 89% respectively.

It is apparent that collaboration now plays an ever growing role in contemporary VOCs research; therefore, it will be taken for a further analysis. Among the 9,810 articles with address information, 52% were publications by single institute, and others were inter-institutional collaborative works, both national (31%) and international (17%) collaborations included. As could be seen from Fig. 2, collaborative articles were more prevalent in recent years than in the earlier years, which went from 29% percentage of world SCI

Table 2 Top 50 most productive countries of articles, 1992–2007

Rank	Country	P (%P)	IP	CP	%C
1	USA	3,690 (38)	2,971	719	19
2	Germany	797 (8.1)	497	300	38
3	UK	639 (6.5)	379	260	41
4	France	579 (5.9)	382	197	34
5	Canada	515 (5.2)	332	183	36
6	Spain	476 (4.9)	359	117	25
7	Japan	469 (4.8)	366	103	22
8	China	420 (4.3)	270	150	36
9	Italy	419 (4.3)	291	128	31
10	Taiwan	344 (3.5)	299	45	13
11	South Korea	323 (3.3)	248	75	23
12	Sweden	224 (2.3)	166	58	26
13	Switzerland	202 (2.1)	107	95	47
14	Poland	186 (1.9)	139	47	25
15	Denmark	181 (1.8)	89	92	51
15	Netherlands	181 (1.8)	86	95	52
17	Finland	180 (1.8)	105	75	42
18	Belgium	176 (1.8)	115	61	35
19	Austria	143 (1.5)	38	105	73
20	Brazil	139 (1.4)	95	44	32
21	Australia	135 (1.4)	80	55	41
22	Greece	134 (1.4)	91	43	32
23	Hong Kong	133 (1.4)	70	63	47
24	India	95 (1.0)	81	14	15
25	Portugal	87 (0.89)	55	32	37
26	Russia	78 (0.80)	37	41	53
27	Norway	74 (0.75)	34	40	54
28	Czech Republic	70 (0.71)	42	28	40
29	Mexico	67 (0.68)	33	34	51
30	Turkey	63 (0.64)	47	16	25
31	Israel	42 (0.43)	17	25	60
32	Slovakia	40 (0.41)	17	23	58
33	Hungary	38 (0.39)	21	17	45
34	Romania	34 (0.35)	13	21	62
35	Iran	33 (0.34)	23	10	30
35	Thailand	33 (0.34)	11	22	67
37	Singapore	31 (0.32)	20	11	35
38	Ireland	30 (0.31)	16	14	47
39	Argentina	26 (0.27)	14	12	46
40	Chile	21 (0.21)	3	18	86
41	South Africa	20 (0.20)	12	8	40
42	New Zealand	17 (0.17)	12	5	29
43	Malaysia	16 (0.16)	14	2	13

Table 2 continued

Rank	Country	P (%P)	IP	CP	%C
44	Egypt	15 (0.15)	9	6	40
44	Kuwait	15 (0.15)	13	2	13
46	Estonia	13 (0.13)	2	11	85
47	Venezuela	12 (0.12)	0	12	100
48	Algeria	11 (0.11)	3	8	73
48	Bulgaria	11 (0.11)	4	7	64
48	Slovenia	11 (0.11)	5	6	55

P publication of the country/territory, *%P* share in publication, *IP* independent publication, *CP* international collaborative publication, *%C* the percentage of international collaborative publication in total publication

Table 3 Top 20 most productive institutes, 1992–2007

Rank	Institute	P (%P)	IP	CP	%C
1	Environmental Protection Agency (EPA), USA	307 (3.1)	83	224	73
2	National Center for Atmospheric Research (NCAR), USA	161 (1.6)	17	144	89
3	University of Colorado, USA	138 (1.4)	26	112	81
4	Chinese Academy of Sciences, China	111 (1.1)	44	67	60
5	University of California Berkeley, USA	109 (1.1)	29	80	73
6	University of Texas, USA	106 (1.1)	42	64	60
7	National Research Council (CNR), Italy	93 (0.95)	19	74	80
8	University of Michigan, USA	89 (0.91)	44	45	51
9	University of Waterloo, Canada	88 (0.90)	54	34	39
10	Consejo Superior de Investigactiones Cientificas (CSIC), Spain	85 (0.87)	34	51	60
11	National Oceanic and Atmospheric Administration (NOAA), USA	84 (0.86)	3	81	96
12	Hong Kong Polytechnic University, Hong Kong	83 (0.85)	34	49	59
13	Georgia Institute of Technology, USA	82 (0.84)	22	60	73
14	University of California Riverside, USA	81 (0.83)	52	29	36
15	Max Planck Institute of Chemistry, Germany	79 (0.81)	12	67	85
16	National Taiwan University, Taiwan	74 (0.75)	26	48	65
17	University of Leeds, UK	69 (0.70)	17	52	75
18	Innsbruck University, Austria	68 (0.69)	4	64	94
19	Centre National de la Recherché Scientifique (CNRS), France	65 (0.66)	19	46	71
19	University of California Davis, USA	65 (0.66)	22	43	66

P publication of the country/territory, *%P* share in publication, *IP* independent publication, *CP* international collaborative publication, *%C* the percentage of international collaborative publication in total publication

articles in 1992 to 57% in 2007. In general, the ascending trend of collaborative article proportion to world publication was somewhat owing to the rising number of institutes and countries that engaged in the research. Simultaneously, the recent proportion of the international articles to the world collaborative articles showed a gradual increase, and the collaborative productivity among countries took the majority, with an overall average 65% of collaboration. Using 4-year intervals to minimize the year-to-year fluctuations, the proportions of international collaborative articles to all collaborative ones were 27%, 32%, 36%, and 36% for the periods 1992–1995, 1996–1999, 2000–2003, and 2004–2007,

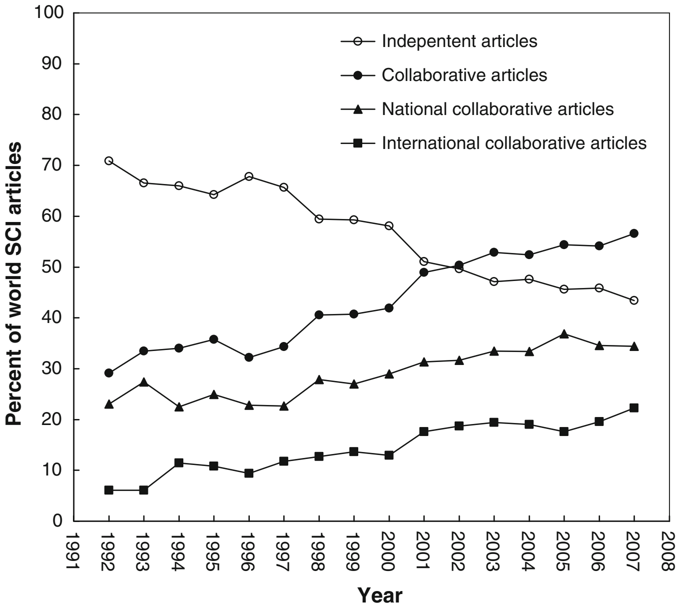

Fig. 2 Independent and collaborative share of articles per year, 1992–2007

respectively. It was obvious that collaborative work of VOCs research shifted from domestic inter-institute to international collaboration.

Publication patterns: subject categories and journals

Based on the classification of subject categories in Journal Citation Report (JCR) of the ISI, the publication output data of VOCs research was distributed in 174 subject categories during the last 16 years. Subject categories containing at least 1,000 articles were environmental sciences (3,565; 36%), environmental engineering (1,728; 17%), meteorology & atmospheric sciences (1,651; 17%), analytical chemistry (1,464; 15%), and chemical engineering (1,307; 17%). These five most productive subject categories, all of which were branches of chemical and environmental science, produced 9,715 articles in total, accounting for 98% of all VOCs publications. From 157 articles in 1992 to 1,032 articles in 2007, environmental sciences were holding primacy all through the study period (Fig. 3). Each of other four subjects also held a sustainable growth trend. As the use of statistics in any scientific discipline could be considered a key element in evaluating its degree of maturity (Palmer et al. 2005), the result provided a current view of the VOCs research patterns.

In total, 9,917 articles were published in a really wide range of 1,295 journals including specialty journals, but also journals of other disciplines which all belong to 174 subject categories above. Table 4 lists the 10 journals with the greatest number of published articles referring to VOCs research from 1992 to 2007. Approximately 28% of the VOCs articles reside in these top 10 most productive journals, whereas the remainders reside in other 1,285 ones. *Atmospheric Environment* ranked first with 738 (7.4%) published papers followed by *Environmental Science & Technology* with 374 (3.8%) publications; while *Analytical Chemistry* and *Applied Catalysis B-Environmental* had a relatively higher impact factor. According to the result of the analysis in subject categories, all the top 10

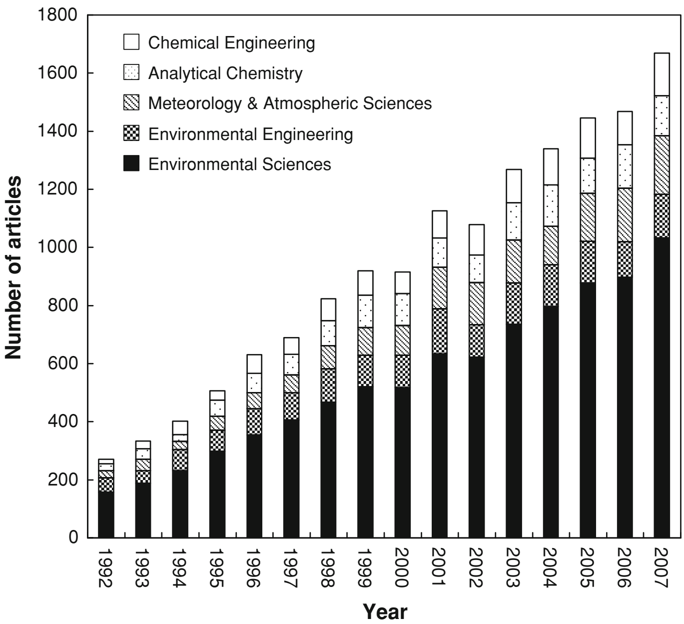

Fig. 3 Publications of the five most productive subject categories, 1992–2007

Table 4 The top 10 most published journals, 1992–2007

Journals	P	%	IF
Atmospheric Environment	738	7.4	2.549
Environmental Science & Technology	374	3.8	4.363
Journal of Geophysical Research-Atmospheres	310	3.1	2.953
Journal of Chromatography A	305	3.1	3.641
Journal of the Air & Waste Management Association	262	2.6	1.523
Chemosphere	166	1.7	2.739
Analytical Chemistry	161	1.6	5.287
Sensors and Actuators B-Chemical	156	1.6	2.934
Applied Catalysis B-Environmental	148	1.5	4.651
Science of the Total Environment	117	1.2	2.182

P publications of the journal, % percentage of the total publications during the past 16 years, *IF* impact factor

journals belong to chemical and environmental research field without exception, indicating that research in chemical and environmental sciences was the mainstream among all VOCs-related fields.

Research emphasis: author keywords, words in title, words in abstract, and keywords plus

The technique of statistical analysis of keywords and title-words may be aimed at discovering directions of science. Especially, author keywords analysis could offer the information of research trends as viewed by researchers (Garfield 1990). In this sense it proved important for monitoring the development of science and programs. Bibliometric methods concerning author keywords analysis can only be found in recent years (Chiu and Ho 2007) and using the author keyword to analyze the trend of research is much less frequent (Ho 2007). The examination of author keywords in this study revealed that 14,490 author keywords were used from 1992 to 2007. These keywords were calculated and ranked by total 16-year study and 4 year-time periods. Table 5 showed the 20 most frequently used author keywords with their rankings and percentages. Except for "volatile organic compounds," "VOC," and "VOCs" which were searching words in this study, the two most frequently used keywords were "ozone" and "benzene". "Toluene" and "adsorption" were also the most popular author keywords in the past 16 years, and both had higher increasing rates in the ranking of frequency. Similarly, the rank of "formaldehyde" went up quickly in the latest decade. Out of the top 20, there were five terms attracting more and more attention in VOCs research: "titanium dioxide/titania/TiO_2," "catalytic oxidation," "catalytic combustion," "photocatalysis," and "electronic nose" (Fig. 4). The extremely high increasing rate in the ranking of author keywords showed their importance and made them the new focus. However, what should be noted was that the analysis in this study was only for a total of 6,300 VOCs articles with author keywords records, accounting for 64% of the publications in the investigated 16 years. Hence, our data were only an approximate reflection of scientific attention.

Table 5 Top 20 most used author keywords, 1992–2007

Author keywords	P	1992–2007 R (%)	1992–1995 R (%)	1996–1999 R (%)	2000–2003 R (%)	2004–2007 R (%)
Volatile organic compounds	1,143	1 (18)	1 (25)	1 (24)	1 (21)	1 (14)
VOC	463	2 (7.3)	2 (6.4)	2 (8.7)	2 (6.8)	3 (7.3)
VOCs	423	3 (6.7)	3 (5.8)	3 (5.7)	3 (6.0)	2 (7.6)
Ozone	206	4 (3.3)	4 (5.0)	4 (4.1)	5 (3.4)	7 (2.7)
Benzene	205	5 (3.3)	25 (1.5)	5 (3.5)	4 (3.9)	6 (3.0)
Toluene	196	6 (3.1)	17 (1.8)	9 (2.8)	6 (3.1)	5 (3.4)
Adsorption	183	7 (2.9)	25 (1.5)	11 (2.5)	9 (2.6)	4 (3.5)
Gas chromatography	171	8 (2.7)	7 (2.9)	7 (3.0)	7 (3.0)	8 (2.4)
Isoprene	139	9 (2.2)	17 (1.8)	10 (2.6)	8 (2.6)	13 (1.9)
Indoor air quality	131	10 (2.1)	35 (1.2)	16 (2.0)	10 (2.2)	10 (2.1)
Volatile organic compounds (VOCs)	131	10 (2.1)	17 (1.8)	13 (2.1)	10 (2.2)	11 (2.0)
Air pollution	124	12 (2.0)	6 (4.4)	12 (2.2)	12 (2.1)	15 (1.5)
Volatile organic compound	124	12 (2.0)	12 (2.0)	16 (2.0)	17 (1.6)	9 (2.2)
Pervaporation	110	14 (1.7)	17 (1.8)	13 (2.1)	14 (1.8)	14 (1.6)
Formaldehyde	101	15 (1.6)	35 (1.2)	41 (1.0)	18 (1.5)	12 (1.9)
Indoor air	101	15 (1.6)	5 (4.7)	18 (1.8)	14 (1.8)	29 (1.0)
Biofiltration	86	17 (1.4)	89 (0.58)	24 (1.5)	18 (1.5)	18 (1.3)
Monoterpenes	86	17 (1.4)	35 (1.2)	27 (1.3)	16 (1.8)	24 (1.1)
Activated carbon	85	19 (1.3)	25 (1.5)	31 (1.2)	22 (1.5)	18 (1.3)
Trichloroethylene	84	20 (1.3)	50 (0.88)	27 (1.3)	18 (1.5)	21 (1.3)

P publications in the study period, *R (%)* rank (percentage of publications containing this author key word)

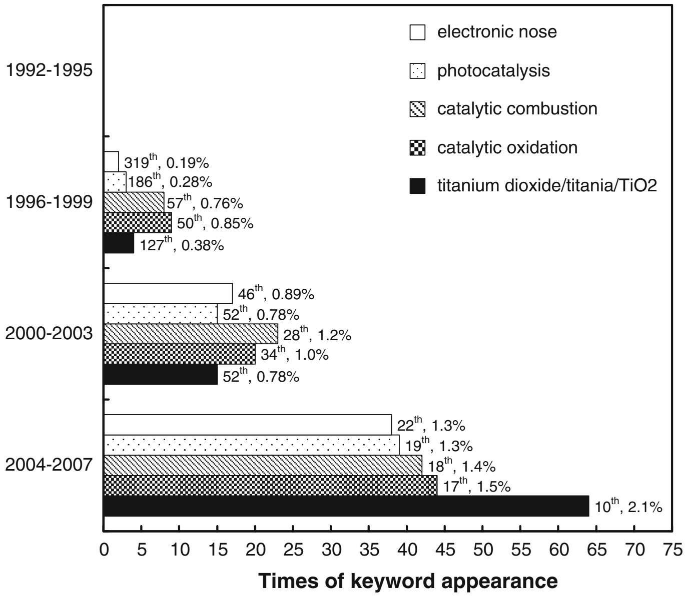

Fig. 4 Frequency of keywords in different period, 1992–2007

An analysis of single words in title and abstract was also undertaken, for it could be used to make inferences of the scientific literature or to identify the subjective focus and emphasis specified by authors. Some prepositions such as "of" and "in", apparently were used frequently during our study period; however, these have no usefulness for the analysis of research trend. Therefore, all these empty words including "of," "in," "and," "the," "a," "for," "with," "by," "using," "high," and "more" were discarded in our analysis. The top 20 most frequently used single words in title and abstract were listed in Tables 6 and 7 respectively. "Emissions/emission," "analysis," "ozone," "indoor," "oxidation," "spectrometry," "carbon," "removal," "exposure," "model," "concentration/concentrations," "method," "chemical," and "toluene" were the most frequently used single words in title and abstract during the period 1992–2007. It can be seen clearly from the two tables that both "oxidation" in title and "toluene" in abstract had a notable increasing trend in the last 16 years. This result agrees with the preceding analysis of author key words. By contrast, the word "water" both in title and in abstract showed a clear decrease during the study period.

The keywords plus in the SCI database supplied additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes (Garfield and Sher 1993). Keywords plus are words or phrases that frequently appear in the titles of an article's references, but do not necessarily appear in the title of the article itself. They may be present for articles that have no author keywords, or may include important terms not listed among the titles, abstracts, or author keywords. In this article, keywords plus were analyzed to substantially augment author-keyword, title-word and abstract-word indexing. Table 8 showed distributions of the top 20 most active keywords plus. Except for "hydrocarbons," "pollutants," "atmosphere," and "degradation", all other 16 words listed in the top 20 of keywords plus also appeared in the top 20 of author-keyword, title-word,

Table 6 Top 20 most used single word in title, 1992–2007

Word in title	P	1992–2007 R (%)	1992–1995 R (%)	1996–1999 R (%)	2000–2003 R (%)	2004–2007 R (%)
Volatile	2,298	1 (23)	1 (30)	2 (27)	2 (23)	2 (20)
Organic	2,184	2 (22)	8 (5.1)	1 (29)	1 (24)	1 (21)
Compounds	1,835	3 (19)	28 (2.5)	3 (24)	3 (21)	3 (18)
Air	1,226	4 (12)	4 (9.2)	4 (14)	4 (13)	4 (12)
Gas	799	5 (8.1)	37 (2.2)	6 (9.3)	5 (8.8)	5 (8.4)
Emissions	785	6 (7.9)	3 (9.3)	7 (8.8)	6 (7.5)	6 (7.4)
Analysis	719	7 (7.3)	7 (6.4)	8 (7.9)	7 (7.5)	7 (7.0)
VOC	711	8 (7.2)	5 (9.1)	5 (9.4)	8 (7.0)	8 (5.8)
VOCs	573	9 (5.8)	6 (6.9)	9 (6.6)	9 (5.5)	9 (5.3)
Water	479	10 (4.8)	9 (5.0)	10 (6.3)	10 (4.9)	15 (4.0)
Ozone	417	11 (4.2)	12 (4.3)	24 (3.0)	11 (4.7)	11 (4.4)
Mass	415	12 (4.2)	208 (0.62)	11 (5.2)	12 (4.5)	12 (4.3)
Emission	408	13 (4.1)	11 (4.7)	12 (4.0)	17 (3.7)	13 (4.3)
Indoor	403	14 (4.1)	10 (4.8)	14 (3.8)	16 (4.0)	15 (4.0)
Oxidation	392	15 (4.0)	115 (0.92)	34 (2.6)	14 (4.2)	10 (5.2)
Spectrometry	365	16 (3.7)	115 (0.92)	19 (3.2)	13 (4.2)	14 (4.2)
Carbon	331	17 (3.3)	70 (1.4)	32 (2.7)	15 (4.1)	17 (3.6)
Removal	318	18 (3.2)	17 (3.6)	24 (3.0)	20 (3.4)	21 (3.1)
Exposure	315	19 (3.2)	12 (4.3)	16 (3.6)	22 (3.1)	30 (2.8)
Model	314	20 (3.2)	17 (3.6)	18 (3.4)	19 (3.4)	29 (2.8)

P publications in the study period, *R (%)* rank (percentage of publications containing this title-word)

or abstract-word, which showed significant agreement. Again, “oxidation” and “toluene” exhibited their rapid growing pace on VOCs research. Meanwhile, “removal” stood out in this group, the frequency of which ranked from 19th in 1992–1995 to 6th in the last 4 years.

From the four parts analysis of keyword above, research emphasis and trends could be roughly found. Being the three most important members of the VOCs’ family, “benzene,” “toluene” and “formaldehyde” were the hotspots of current research (Norback et al. 1995; Wallace 1996; Przyjazny and Kokosa 2002). The high growing rates of “removal,” “adsorption,” “oxidation,” “catalytic oxidation,” “catalytic combustion,” “photocatalysis,” and “titanium dioxide/titania/TiO_2” in keywords indicated that researches on VOCs’ removal especially using adsorption techniques and oxidation methods, including catalytic oxidation, catalytic combustion, and photocatalysis especially by TiO_2, was focused more (Brasquet and Le Cloirec 1997; Jenkin et al. 1997; Ku et al. 2001; Scire et al. 2003; van der Bruggen and Vandecasteele 2003). Meanwhile, detection and analysis of VOCs also received additional spikes of attention (Machado et al. 2005), which could be concluded by the fast increasing appearances of keyword “electronic nose”. Furthermore, compared with water, research in the field of air was the mainstream, and the attention paid to water research decreased slightly in the nearest 16 years.

Table 7 Top 20 most used single word in abstract, 1992–2007

Word in abstract	P	1992–2007 R (%)	1992–1995 R (%)	1996–1999 R (%)	2000–2003 R (%)	2004–2007 R (%)
Organic	6,072	1 (63)	1 (75)	1 (66)	1 (63)	1 (59)
Compounds	5,757	2 (60)	3 (69)	3 (61)	2 (60)	2 (57)
Volatile	5,739	3 (60)	2 (71)	2 (62)	3 (60)	3 (56)
Air	3,448	4 (36)	4 (38)	4 (37)	4 (36)	4 (34)
VOCs	3,055	5 (32)	6 (35)	5 (34)	5 (31)	5 (31)
Concentrations	2,791	6 (29)	7 (31)	7 (29)	6 (29)	6 (28)
VOC	2,778	7 (29)	5 (36)	6 (32)	8 (28)	8 (26)
Gas	2,713	8 (28)	8 (29)	8 (28)	7 (28)	7 (28)
Concentration	2,322	9 (24)	11 (22)	9 (23)	9 (25)	9 (24)
Analysis	2,151	10 (22)	13 (20)	11 (22)	10 (22)	10 (23)
Model	1,962	11 (20)	10 (22)	12 (20)	12 (21)	11 (20)
Emissions	1,933	12 (20)	11 (22)	13 (20)	11 (21)	12 (19)
Conditions	1,800	13 (19)	19 (15)	14 (19)	13 (19)	14 (19)
Method	1,783	14 (19)	14 (20)	15 (18)	14 (18)	15 (19)
Water	1,686	15 (18)	9 (26)	10 (22)	20 (16)	24 (14)
Temperature	1,680	16 (17)	25 (13)	18 (16)	15 (17)	13 (19)
Chemical	1,584	17 (16)	21 (14)	20 (15)	19 (16)	16 (18)
Samples	1,576	18 (16)	16 (16)	17 (16)	16 (17)	19 (16)
Emission	1,554	19 (16)	22 (14)	19 (15)	17 (17)	17 (17)
Toluene	1,429	20 (15)	49 (9.2)	23 (14)	21 (15)	18 (16)

P publications in the study period; *R (%)* rank (percentage of publications containing this abstract-word)

Conclusion

In this study dealing with VOCs SCI papers, we obtained some significant points on the worldwide research trends throughout the period from 1992 to 2007. The effort provided a systematically structural picture, as well as clues to the impacts of the VOCs topic. English was by far the dominant language; while 16 other languages were used as well; therefore, this indicated that VOCs research became more globally concerned. Along with the development of SCI, VOCs research publication continually grew in the last century and started to go up significantly in 1980s; meanwhile, more countries and institutes engaged in VOCs research. Collaborative articles had shifted from domestic collaboration to international collaboration over the years. USA contributed the most VOCs articles followed by Germany and the UK; however, Austria owned the highest collaboration rate, for 73% of its publications were collaborated with other countries. Of all the institutes participating in VOCs research, US Environmental Protection Agency (EPA) held primacy over the most publications. The mainstream of VOCs research was in the environmental and chemical related fields. As the flagship journal of the field, *Atmospheric Environment* published most of the articles. Finally, benzene, toluene, and formaldehyde were the recent emphasis of VOCs research; besides, detection and removal, especially by adsorption technique and oxidation method, of VOCs were to be the orientation of all VOCs research in the next few years. Moreover, research in the field of water was less concerned than that of air and has slightly decreased in the latest 16 years.

Table 8 Top 20 most used key words plus, 1992–2007

Keywords plus	P	1992–2007 R (%)	1992–1995 R (%)	1996–1999 R (%)	2000–2003 R (%)	2004–2007 R (%)
Volatile organic-compounds	2,564	1 (30)	1 (16)	1 (23)	1 (30)	1 (36)
Air	737	2 (8.8)	3 (9.4)	3 (10)	2 (8.7)	2 (8.3)
Water	619	3 (7.4)	2 (16)	2 (11)	4 (7.1)	7 (4.7)
Emissions	510	4 (6.1)	13 (3.0)	7 (4.3)	3 (7.3)	3 (6.5)
Hydrocarbons	494	5 (5.9)	4 (6.0)	4 (5.7)	5 (6.9)	4 (5.2)
Removal	372	6 (4.4)	19 (2.3)	9 (4.0)	8 (4.2)	6 (5.0)
Model	366	7 (4.3)	16 (2.5)	5 (5.4)	6 (4.4)	9 (4.2)
Ozone	359	8 (4.3)	6 (4.3)	6 (4.5)	7 (4.3)	9 (4.2)
Exposure	353	9 (4.2)	5 (5.3)	8 (4.1)	10 (3.8)	8 (4.3)
Oxidation	324	10 (3.8)	109 (0.66)	18 (2.6)	11 (3.5)	5 (5.1)
VOCs	287	11 (3.4)	31 (1.8)	14 (3.0)	12 (3.4)	12 (3.8)
Gas-chromatography	271	12 (3.2)	9 (3.3)	10 (3.7)	14 (3.4)	19 (2.9)
Toluene	263	13 (3.1)	31 (1.8)	20 (2.4)	19 (2.7)	11 (3.9)
Organic-compounds	259	14 (3.1)	9 (3.3)	12 (3.5)	12 (3.4)	24 (2.6)
Chemistry	257	15 (3.1)	37 (1.7)	26 (2.2)	9 (3.8)	17 (3.1)
Pollutants	254	16 (3.0)	7 (4.0)	11 (3.6)	17 (2.8)	23 (2.8)
Adsorption	235	17 (2.8)	19 (2.3)	20 (2.4)	20 (2.5)	15 (3.2)
Atmosphere	234	18 (2.8)	16 (2.5)	27 (2.1)	15 (3.1)	19 (2.9)
Benzene	234	18 (2.8)	23 (2.1)	23 (2.3)	23 (2.3)	14 (3.4)
Degradation	207	20 (2.5)	28 (2.0)	57 (1.1)	17 (2.8)	22 (2.9)

P publications in the study period; *R (%)* rank (percentage of publications containing this keyword plus)

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