Science of the Total Environment 473–474 (2014) 483–489

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

A bibliometric analysis of research on the risk of engineering nanomaterials during 1999–2012

Qiang Wang [a], Zhaoguang Yang [a,b], Yuan Yang [a], Chenlu Long [a], Haipu Li [a,*]

[a] Center for Environment and Water Resources, School of Chemistry & Chemical Engineering, Central South University, No. 392 Lushan Nan Road, Yuelu District, Changsha 410083, PR China
[b] Shenzhen Graduate School, Central South University, B406 Virtual University, Shenzhen High-tech Industrial Pk, Shenzhen Guangdong 518057, PR China

HIGHLIGHTS

- Research on the risk of engineering nanomaterials was characterized based on SCI-Expanded during 1999–2012.
- Research emphases were obtained through synthesized analysis by co-citation and words from author keywords.
- Health effect and nanotoxicology of engineering nanomaterials were common research issues.
- Environmental behavior and ecological risk of engineering nanomaterials are getting popular.

ARTICLE INFO

Article history:
Received 16 November 2013
Received in revised form 12 December 2013
Accepted 14 December 2013
Available online 3 January 2014

Keywords:
Bibliometric
SCI-Expanded
Engineering nanomaterials
Risk
Environmental behavior

ABSTRACT

A bibliometric analysis based on the Science Citation Index Expanded (SCI-Expanded) from the Web of Science was carried out to provide insights into research activities and tendencies of the global risk of engineering nanomaterials (ENMs) from 1999 to 2012. The number of publications per year has increased steadily since approximately 2006. The USA produced 41.9% of all pertinent articles followed by China with 14.8% and UK with 9.1%. *Environmental Science & Technology*, *Toxicology*, and *Journal of Nanoparticle Research* were the three most common journals in this field. A synthesized analysis by co-citation and words from author keywords provided the clues to discover the current research emphases. The mainstream research related to risk of ENMs was toxicological effects and ecological risk. Toxicity effect strongly promoted the development of related research in the past 14 years. Research on environmental behavior and ecological risk of ENMs is the fast growing field.

1. Introduction

Nanotechnology as a driving force for a new economy, is revolutionizing the chemical, telecom, biotech, pharmaceutical, health care, aerospace, and computer industries, and many exciting new nanotech applications are envisioned for the near future (Maynard et al., 2006). According to the report of the U.S. National Science Foundation (NSF), the nanotechnology-related product market was predicted to be over one trillion dollars by 2015 (Hullmann, 2007). Nanotechnology has become a top priority in governments, the private sector and the public all over the world (Roco, 2003).

Engineered nanomaterials (ENMs) are manufactured materials having at least one dimension in the nanoscale (ca. 1–100 nm) dimension. The nanotechnology field continues to grow rapidly and the increasing use of ENMs in commercial products translates into an increasing presence in the biosphere (Lowry et al., 2012; Wiesner et al., 2006; Mueller and Nowack, 2008). While the nanoscale dimensions give ENMs new characteristics, the potential for their release in the environment and subsequent effects on ecosystem health is becoming an increasing concern (Yang et al., 2009; Gottschalk and Nowack, 2011). Studies have suggested that the released nanomaterials can affect biological behaviors at the cellular, subcellular and protein levels (Nel et al., 2006; Colvin, 2003; Donaldson et al., 2006; Owen and Handy, 2007). Moreover, some nanoparticles readily travel throughout the body, deposit in target organs, penetrate cell membranes, lodge in mitochondria, and may trigger injurious responses (Oberdoster et al., 2005; Kreyling et al., 2002; Semmler et al., 2004; Åkerman et al., 2002; Rejman et al., 2004). Therefore, their risk assessment should be evaluated to make proper prevention and control countermeasures. As research in the field of risk from ENMs is attracting increasing attention, it is urgent to portray the global trend of the research fields that sustain human life.

Bibliometrics is a useful tool to map the literature around a research field. It refers to research methodology employed in library and information sciences, which utilizes statistics and quantitative analysis methods to describe distribution patterns of articles with a given topic, field, institute or country. These methods have recently been employed to investigate research trends of specific fields (Braun et al.,

* Corresponding author. Tel.: +86 731 88876961; fax: +86 731 88876960.
E-mail address: lihaipu@csu.edu.cn (H. Li).

0048-9697/$ – see front matter
http://dx.doi.org/10.1016/j.scitotenv.2013.12.066

1995; Ho, 2008; Li et al., 2009a, 2009b). An assumption was made in these studies that the research publications of a country in a certain scientific subfield reflect its commitment to the state of science and is a reasonable indicator for research and development efforts in that field. However, there are some universal deficiencies in traditional bibliometrics analysis in scientific research fields. Many studies only select several journals or categories to represent global research trends related to a certain topic (Mela and Cimmino, 1998; Klein and Hage, 2006). The change in citations or publication counts of countries and organizations cannot completely indicate the development trend or future orientation of research field (Chiu and Ho, 2007). More information like source title (Li et al., 2009a, 2009b), author keyword (Ugolini et al., 2001), keyword plus (Qin, 2000), abstracts (Zhang et al., 2010) and funding agencies (Wang et al., 2012) should be introduced into the research trend study.

Research related with risk of ENMs during the past 14 years was analyzed to provide a basis for a better understanding of the global research situation, establishing long term strategies for this field. The analyzed aspects covered not only the quantitative description of publications, including annual outputs, mainstream journals, Web of Science categories, leading countries and institutions, funding agencies, but also the research tendencies and hotspots obtained from the synthesized analysis by co-citation and words in author keywords.

2. Methodology

The methodology used in this research was similar to other bibliometric studies (Chiu et al., 2004; Hirsch, 2005). Data were obtained from the online version of SCI-Expanded databases of the Web of Science from Thomson Reuters on 13th July 2013. According to the Journal Citation Reports (JCR), it indexes 8471 major journals with citation references across 176 scientific disciplines in 2012.

For bibliometric analysis, the online version of SCI-Expanded was searched with keywords (nanomaterial* or "nano-metal oxide*" or "nano metal*" or nanotube*or "quantum dot*" or C_{60} or C_{70} or fullerene* or SWCNTs or MWCNTs or nano-Ag or nano-Au or nano-Cu or nano-Al or nano-Fe or nano-Ti or nano-Zn or nano-CdSe or nano-ZnS or nano-CdTe or nano-TiO_2 or nano-Al_2O_3 or nano-Fe_2O_3 or nano-Fe_3O_4 or nano-ZnO or nano-CuO or nano-silver or "nano $ZnFe_2O_4$") and (risk or "environmental exposure" or "health effect" or "environmental behavior" or "toxicity assess*" or nanotoxicology or nanotoxicity or ecotoxicity) to compile a bibliography of all articles related to the research in the field of risk from ENMs. As journal articles represented the majority of document types that also included whole research ideas and results (Ho et al., 2010), only journal articles were searched for bibliometric analysis as the relevant citable items. Altogether 901 original articles were used for further analysis.

Downloaded information included names of authors, contact address, title, year of publication, author keywords, keywords plus, abstract, funding agencies, Web of science categories of the article, and names of journals publishing the articles. The records were downloaded into spreadsheet software. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as from the United Kingdom (UK). Contributions of different institutions and countries were estimated by the affiliation of at least one author to the publications, where the term "single country article" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from multiple countries. The term "single institution article" was assigned if the researchers' addresses were from the same institution. The term "inter-institutionally collaborative article" was assigned if authors were from different institutions (Fu et al., 2013). Citespace 3.5 was applied in the co-citation analysis (Chen, 2004, 2006). It can help to identify the most popular words used in articles over a particular period of time. Relevant parameters in citespace program for co-citation analysis were set as follows: the thresholds were (3, 2, 15), (4, 3, 19) and (4, 3, 20); Reference was chosen as the node; Title, abstract, descriptor and identifiers were chosen as sources; None was chosen as term. Minimum Spanning Tree (MST) was employed in network pruning. The slice length was 2-year. 683 nodes and 1011 links were obtained to compose the co-citation map after running the program.

3. Results and discussion

3.1. Performance of publication

3.1.1. Publication outputs

To obtain an overview of ENMs' risk research, the annual number of articles during 1999–2012 was displayed in Table 1. The number of ENMs risk publications increased from 1 in 1999 to 256 in 2012, with the total publications reaching 901. The number of publications per year has increased steadily since approximately 2006. And the average article lengths fluctuated slightly, with an overall average of 8.2 pages. 10.0 references were cited per article in 1999, comparing to 45.8 references per article in 2012, with slight increases through-out the 14 years. An increasing number of authors carrying out research on risk of ENMs from 3 in 1999 to 1473 in 2012, the average number of authors of a single article was 4.3.

3.1.2. Publication distribution of countries, institutions and funding agencies

The analysis of author's countries/territories was based on journal articles in which the address and affiliation of at least one author were provided. It was noted that the SCI had a policy of omitting certain addresses (e.g. those preceded by the phrase "on leave from"). There were 10 articles without any author address information on ISI Web of Science and the total article number for distribution analysis of country and institute publications was 891. Of all the articles with author address, 695 (78.0%) were single country articles and 196 (22.0%) were internationally collaborative articles. Table 2 shows the top 20 countries/territories ranked by the number of total publications with other information: the number and percentage of single country articles and internationally collaborated articles, as well as first author and corresponding author articles.

The contribution of different institutions was estimated by the institution of the affiliation of at least one author of the published papers. The top 10 institutions in the past 14 year period are displayed in Table 3. Among the top 10 institutions, 6 were in the United States, 2 were in China and one each in Switzerland and Denmark. Leading was the Chinese Academy of Sciences with 43 articles, followed by the National Institute for Occupational Safety and Health of United States (NIOSH, USA; 31) and the Swiss Federal Laboratories for Materials (EMPA; 22) from Switzerland. The Chinese Academy of Sciences also

Table 1
Characteristics by year of publication outputs from 1999 to 2012.

PY	TP	AU	AU/TP	PG	PG/TP	NR	NR/TP
1999	1	3	3.0	5	5.0	10	10.0
2001	1	2	2.0	4	4.0	16	16.0
2004	3	5	1.7	27	9.0	64	21.3
2005	8	40	5.0	64	8.0	258	32.3
2006	30	111	3.7	268	8.9	1116	37.2
2007	51	284	5.6	483	9.5	1858	36.4
2008	90	429	4.8	792	8.8	3298	36.6
2009	90	440	4.9	773	8.6	3627	40.3
2010	148	749	5.1	1428	9.6	6780	45.8
2011	223	1246	5.6	1992	8.9	9908	44.4
2012	256	1473	5.8	2583	10.1	11716	45.8
Average			4.3		8.2		33.3

PY: published year; TP: total articles; AU: author number; AU/TP: author number per article; PG: page count; PG/TP: page count per article; NR: cited reference count; NR/TP: cited reference count per article.

Table 2
Most productive countries in research in the field of risk from ENMs during 1999–2012.

Country	TPR (%)	SPR (%)	CPR (%)	FPR (%)	RPR (%)
USA	373 (41.9)	1 (37.7)	1 (56.6)	1 (34.6)	1 (34.7)
China	132 (14.8)	2 (11.2)	2 (27.6)	2 (12.5)	2 (12.5)
UK	82 (9.1)	5 (4.3)	3 (26.0)	5 (4.6)	5 (4.6)
Italy	54 (6.1)	4 (4.7)	6 (10.7)	3 (5.3)	3 (5.3)
Germany	53 (5.9)	7 (3.3)	4 (15.3)	7 (3.4)	7 (3.4)
Switzerland	48 (5.4)	6 (4.0)	7 (10.2)	6 (4.2)	6 (4.3)
Japan	47 (5.3)	3 (5.2)	10 (5.6)	4 (4.9)	4 (4.9)
South Korea	36 (4.0)	7 (3.3)	9 (6.6)	7 (3.4)	7 (3.4)
France	35 (3.9)	12 (1.7)	5 (11.7)	11 (2.1)	11 (2.1)
Canada	31 (3.5)	7 (3.3)	13 (4.1)	9 (3.1)	9 (3.1)
Netherlands	30 (3.4)	12 (1.7)	8 (9.2)	12 (2.0)	12 (2.0)
Denmark	26 (2.9)	11 (2.2)	10 (5.6)	12 (2.0)	12 (2.0)
India	22 (2.5)	10 (2.3)	18 (3.1)	10 (2.4)	10 (2.5)
Australia	19 (2.1)	15 (1.2)	10 (5.6)	14 (1.5)	14 (1.5)
Finland	15 (1.7)	14 (1.3)	18 (3.1)	15 (1.2)	15 (1.2)
Spain	14 (1.6)	18 (0.9)	13 (4.1)	18 (1.0)	18 (1.0)
Belgium	14 (1.6)	16 (1.0)	15 (3.6)	17 (1.1)	17 (1.1)
Sweden	13 (1.5)	18 (0.9)	15 (3.6)	19 (0.9)	19 (0.9)
Brazil	12 (1.3)	18 (0.9)	18 (3.1)	19 (0.9)	19 (0.9)
Poland	11 (1.2)	18 (0.9)	21 (2.6)	19 (0.9)	19 (0.9)

TP: Total publications; SPR: Single country publication rank; CPR: International collaboration publication rank; FPR: First author publication rank; RPR: Corresponding author publication rank.

published the most independent, collaborative, first authored, and corresponding authored articles. However, the Chinese Academy of Sciences has over 100 branches in different cities, and articles divided into branches would result in different rankings (Fu et al., 2013).

In order to investigate the status of main funding sources in this field, the funding information were also collected from the ISI Web of Science database. As the names for funding agencies often have many ways of writing, for example, the National Natural Science Foundation of China, which is the most important funding agency in China, was named as NSFC, NSF of China, Natural Science Foundation of China as well, the names of funding agencies were distinguished one by one to get the accurate result. There were 350 articles without any funding information and the total article number of publications for distribution analysis of funding sources was 551, which were financially supported by 690 funding agencies. Table 4 shows the top 10 productive funding sources, accounting for approximately 64.4% of the articles. The National Science Foundation (NSF, USA; 72), the National Natural Science Foundation of China (NSFC, China; 69) and the US Environmental Protection Agency Science (EPA, USA; 48) were the top three productive funding agencies. However, the times cited per article supported by the National Institute of Health (NIH, USA; 34.2) and the National Science Foundation (NSF, USA; 32.2) were much higher than that of other funding agencies.

3.1.3. Distribution of output in subject categories and journals

In total, 901 articles were published in a wide range of 97 subjects. Among these subjects, 76 (78.4%) subjects contained less than 10 articles. Fig. 1 shows the top 10 productive subjects, accounting for approximately 76.1% of the articles. All the number of articles in these ten subject categories grew quickly since approximately 2006. The subject category of Environmental sciences contributed the most with 285 (15.0%) articles, followed by Toxicology (270; 14.2%) and Nanoscience & Nanotechnology (222; 11.7%). According to the category description in the Web of Science (http://admin-apps.webofknowledge.com/JCR/static_html/scope_notes/SCIENCE/2012/SCOPE_SCI.htm), environmental sciences covers resources concerning many aspects of the study of the environment, such as environmental contamination and toxicology, environmental health, environmental monitoring, environmental geology, and environmental management. Toxicology covers resources that focus on the identification, biochemistry, and effects of harmful substances, including the side effects of drugs, in animals, humans, and the environment. And Nanoscience & Nanotechnology includes resources that focus on basic and applied research at the micro and nano levels across a variety of disciplines including chemistry, biology, bioengineering, physics, electronics, clinical and medical science, chemical engineering and materials science. The three most productive categories have been taking the lead, and are unlikely to be exceeded by other categories in the foreseeable future, which mainly take focus on the toxicology and environmental risk from ENMs.

Table 5 shows the distribution of output in journals. The total of 901 articles were published in 260 journals. *Environmental Science &Technology* (TP = 73; 8.1%), *Nanotoxicology* (TP = 48; 5.3%) and *Journal of Nanoparticle Research* (TP = 42; 4.7%) are the top three journals with the most publications of research on ENMs' risk, which account only 18.1% of all the publications. The percentage of the top productive journal was not high, which indicates the breadth of article distribution as well as the broad interest in risk of ENMs from various research angles. Similar phenomenon also happens in other environment related research areas, such as Water Research in biosorption field (19%) (Ho, 2008) and *Geophysical Research Letters* in global climate change area (3.0%) (Li et al., 2011). Since 2006, the number of articles in all the top five journals grew quickly (Fig. 2), it reveals that the risk problems of ENMs are attracting increasing attention.

3.2. Hot issues and research trends

To capture the hot issues and major research trends, co-citation analysis, as well as author keywords analysis were performed. Co-citation means that two articles are both cited by one identical paper. In co-citation theory, the strength of co-citation between cited articles reflects the inherent association they possessed, and the most co-cited article was believed to be the earliest or most populated work in this field, therefore, the emergence of a most co-cited article was always thought to be the pioneer or milestone, by which we can divide the whole research lifecycle into several stages with respective hot issue. The result of co-citation cluster is illustrated in Fig. 3. Rings with gradient color represent the individual articles, and their association was expressed by their connection lines between them. The color darkness

Table 3
Most productive institutions in research in the field of risk from ENMs during 1999–2012.

Institutions	TPR (%)	SPR (%)	CPR (%)	FPR (%)	RPR (%)
Chinese Academy of Sciences, China	43 (4.8)	1 (3.7)	1 (5.6)	1 (3.3)	1 (3.2)
National Institute for Occupational Safety and Health, USA	31 (3.5)	4 (2.4)	2 (4.3)	2 (2.2)	2 (2.2)
Swiss Federal Laboratories for Materials Science and Technology, Switzerland	22 (2.5)	1 (3.7)	15 (1.6)	3 (2.1)	3 (2.1)
Rice University, USA	21 (2.4)	3 (2.7)	7 (2.1)	5 (1.2)	5 (1.2)
United States Environmental Protection Agency, USA	20 (2.2)	28 (0.5)	3 (3.5)	5 (1.2)	5 (1.2)
Zhejiang University, China	19 (2.1)	28 (0.5)	4 (3.3)	5 (1.2)	5 (1.2)
Duke University, USA	19 (2.1)	10 (1.1)	5 (2.9)	5 (1.2)	5 (1.2)
University of Massachusetts, USA	18 (2.0)	8 (1.3)	6 (2.5)	10 (1.0)	10 (1.0)
Technical University of Denmark, Denmark	17 (1.9)	6 (1.6)	7 (2.1)	5 (1.2)	5 (1.2)
University of Michigan, USA	15 (1.7)	10 (1.1)	7 (2.1)	19 (0.7)	19 (0.8)

TP: Total publications; SPR: Single institute publication rank; CPR: Inter-institutionally collaboration publication rank; FPR: First author publication rank; RPR: Corresponding author publication rank.

Table 4
Most productive funding agencies in research in the field of risk from ENMs during 1999–2012.

Funding agencies	TP	R (%)	TC	TP/TC
National Science Foundation, USA	72	1 (13.1)	2318	32.2
National Nature Sciences Foundation of China	69	2 (12.5)	1059	15.3
Environmental Protection Agency, USA	48	3 (8.7)	1152	24.0
European Commission, European Union	45	4 (8.2)	800	17.8
National Institutes of Health, USA	29	5 (5.3)	993	34.2
National Basic Research Program of China	26	6 (4.7)	454	17.5
National Institute of Environmental Health Sciences, USA	21	7 (3.8)	508	24.2
Chinese Academy of Sciences	17	8 (3.1)	404	23.8
Natural sciences and Engineering Research Council of Canada	15	9 (2.7)	254	16.9
Ministry of Education, Culture, Sports, Science and Technology of Japan	13	10 (2.4)	189	14.5

TP: Total publications; R: Rank; TC: Times cited; TC/TP: Times cited per article.

denotes the year that co-citing occurred, a lighter darkness indicates a co-citating that occurred in earlier years. The radius of tree-ring is proportional to the number of co-citing articles during 1999–2012. The larger a citation tree-ring is, the higher the influence it has. The rings in Fig. 3 indicate that the common intellectual base of research on risk of engineering nanomaterials mainly emerged after 2003. The earlier research did impose some influences on the current researches, but not as high as the research during 2003–2008. Usually, the most co-cited references (the most centralized and prominent rings) are believed to be the most fundamental or popular work in this field, and they are always the groundbreaking discoveries and breakthroughs in this area. Thus, the loose cluster of early publications suggests that few groundbreaking discoveries and breakthroughs have been found until 2003. There are two clear clusters in Fig. 3, revealing there are two categories of topics in the ENMs research field. Cluster 1 is composed with Hyung et al. (2007), Klaine et al. (2008), Mueller and Nowack (2008) and so on, their common research topic is about environmental behavior and ecotoxicity of ENMs. Cluster 2 is composed with Oberdoster et al. (2005), Nel et al. (2006), Law et al. (2004) and so on, their common research topic is about health effect and nanotoxicology of ENMs. These documents suggest that the mainstream of ENM study is environmental risk and nanotoxicology. This conclusion is also confirmed by Fig. 4. For Fig. 4 the tree-rings are arranged chronologically in both vertical and horizontal manner. A diagonal arrangement was designed for ease of viewing. The year of first co-citation was denoted by the color darkness of line connecting two rings, while the number of co-citing articles during this period is proportional to the thickness of a citation tree-ring. The color darkness represents the year that co-citing occurred. For each citation tree-ring, the size quantifies the influence it has. There are five most co-cited works: airborne nanoparticles' health toxicology (Oberdoster et al., 2005), ENMs' ecology toxicology (Nel et al., 2006), pulmonary toxicity of single-wall carbon nanotubes in mice (Law et al., 2004; Warheit et al., 2004) and fullerenes induce oxidative stress in the brain of juvenile Largemouth Bass (Oberdorster, 2004) were researched and reviewed in these papers. It reviews that nanomaterials' toxicology is the basic starting point for most of related research. Meanwhile, ENMs' environmental behavior, bioavailability, environmental exposure and impact study are becoming another hot topic (Hyung et al., 2007; Klaine et al., 2008; Mueller and Nowack, 2008).

At the same time, author keywords generalize the major attention of a research, therefore, one can identify and quantify the research trend of a certain field by simply analyzing the most frequently used author keywords. Bibliometric method through author keywords analysis in a specific period has been developed for a couple of years, and has proved to be a helpful method in revealing the research hotspots and discovering scientific research trends (Chiu and Ho, 2007; Xie et al., 2008; Li et al., 2009a, 2009b). Examination of author keywords in this study period revealed that 1874 author keywords were used. Table 6 shows the top 30 most frequently used author keywords appeared in articles of ENMs' risk field during 1999–2012, with combination of their plural forms, abbreviations, and other transformations. Apart from the search words we used before, like “nanoparticles/nanoparticle”, “nanomaterials/nanomaterial”, “carbon nanotubes/carbon nanotube”, “titanium dioxide/TiO_2” and “risk assessment”, the most frequently used keywords are “nanotoxicology”, “toxicity”, “aggregation”, “ecotoxicity”, “exposure assessment” and so on.

Based on these analysis, the research in the field of risk from ENMs can be divided into two categories: health effect and nanotoxicology

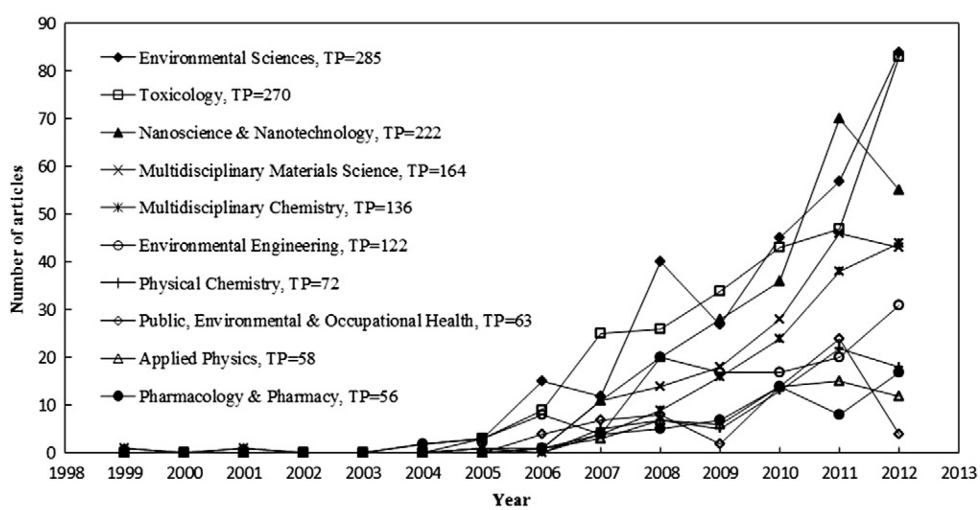

Fig. 1. Publications of the top ten productive Web of Science categories during 1999–2012.

Table 5
Distributions of the output in journals from 1999 to 2012.

Journals	IF*	TP	R (%)
Environmental Science & Technology	5.257	73	1 (8.1)
Nanotoxicology	7.844	48	2 (5.3)
Journal of Nanoparticle Research	2.175	42	3 (4.7)
Environmental Toxicology and Chemistry	2.618	32	4 (3.6)
ACS Nano	12.061	28	5 (3.1)
Science of the Total Environment	3.258	21	6 (2.3)
Journal of Hazardous Materials	3.925	18	7 (2.0)
Toxicology	4.017	16	8 (1.8)
Toxicological Sciences	4.328	15	9 (1.7)
Chemosphere	3.137	14	10 (1.6)

IF: Impact factor (2012); TP: Total publication.

(“nanotoxicology”, “nanotoxicity”, “toxicity” et al.), environmental behavior and ecotoxicity (“environment”, “aggregation”, “exposure assessment” et al.).

3.2.1. Health effect and nanotoxicology

It is well known that ENMs can cause adverse reactions to the body in several organ systems, biological cells and reproductive genetic (Maynard et al., 2006). Since service for the first time revealed nanotoxicity (Service, 2003), the research about health effect and toxicology of ENMs increased rapidly during the period from 2003 to 2007 (Ashikaga et al., 2000; Tachikawa et al., 2007). This was reflected by the continuously increasing number of total publications in this period. The research during this period focuses on how human or animal being affected by ENMs exposure. For example, after 60 days dermal exposure in hairless mice, nano-TiO_2 particles can penetrate through the skin, reach different tissues and induce diverse pathological lesions in several major organs (Wu et al., 2009). Production of increased reactive oxygen species (ROS) is considered as the most common pathway for ENMs induced toxicity (Nel et al., 2006). High ROS levels are indicative of oxidative stress, and can damage cells by peroxidizing lipids, inducing inflammation, altering proteins and DNA, as well as interfering with signaling and gene functions (Lin and Xing, 2007). The molecular mechanism is another reason to explain the toxic effect. Upon exposure, ENMs can easily enter cells by direct penetration or receptor-mediated endocytosis, and are then translocated into different organelles. The ENMs may then interact with intracellular components such as proteins, lipids, or nucleic acids.

3.2.2. Environmental behavior and ecotoxicity

The increase in the production and use of engineered nanomaterials makes exposure of the natural environment to these compounds more and more likely, and the discussion about the potential adverse effects of ENMs has increased steadily in recent years (Nowack and Bucheli, 2007). As assessing the risks of these ENMs in the environment requires an understanding of their mobility, reactivity, ecotoxicity and persistency, the research focus of ENMs's risk field was shifted to their environmental behavior and ecotoxicity. As a result, agglomeration, migration, and pollution sources of ENMs become new hot issues. As agglomeration behavior affect the nano-particle size which is related with the settlement, migration and cytotoxicity of ENMs, agglomeration has become one of the most important topic in this field (Limbach et al., 2005; Chithrani et al., 2006; Lyon et al., 2006; Pan et al., 2007).

Chen and Elimelech (2006) investigated the aggregation and deposition kinetics of fullerene C_{60} nanoparticles over a wide range of monovalent and divalent electrolyte concentrations (Chen, 2006). Since then, agglomeration behavior in water became a very active research aspect and many related articles were published (Chen and Walker, 2007; Saleh et al., 2008; Keller et al., 2010; Saleh et al., 2010). Other hot issues include determination of ENMs in natural environment (Hassellöv et al., 2008), migration and transformation of ENMs through porous media (Lecoanet et al., 2004), interaction mechanism with other pollutants (Nowack and Bucheli, 2007), environment exposure assessment and bioavailability of ENMs. It resulted in a huge increase of publications during 2006–2012 (Table 1) and a rapid publication increase in the subject category of environmental sciences since 2006 (Fig. 1).

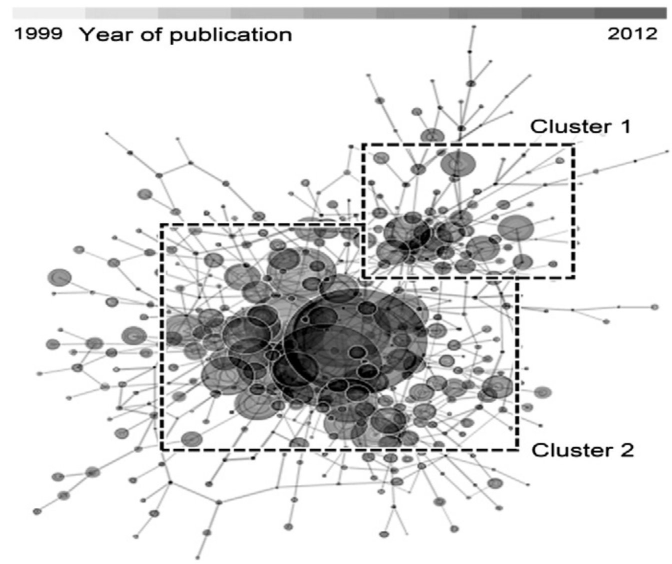

Fig. 3. Cluster analysis of documents based on Citespace.

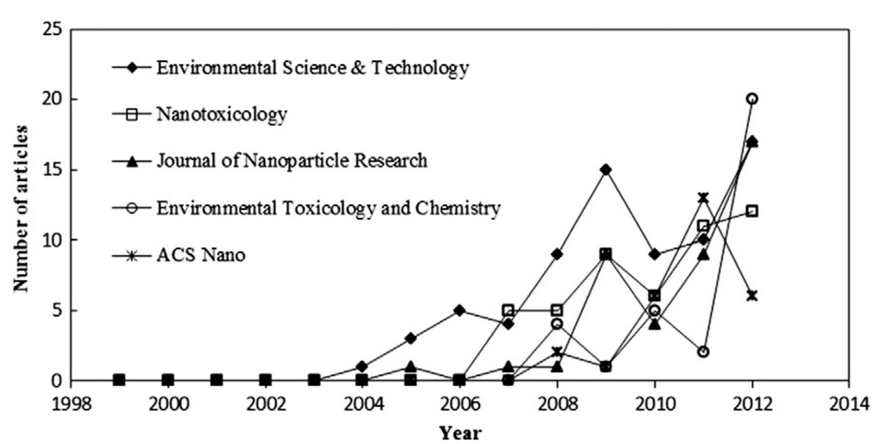

Fig. 2. Publications of the top five most productive journals during 1999–2012.

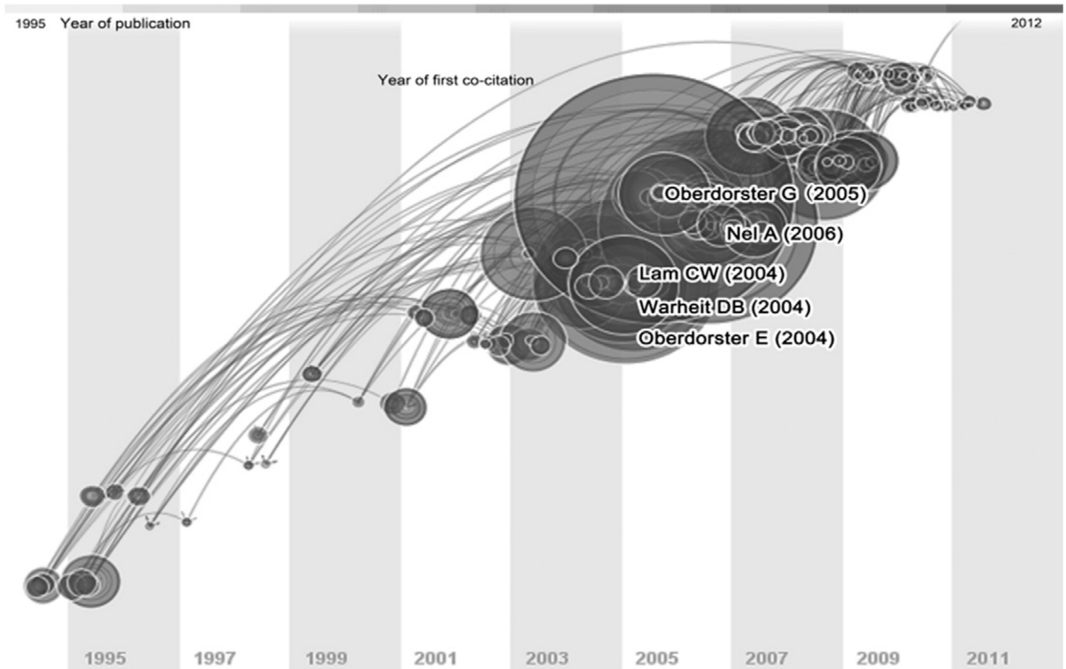

Fig. 4. Co-citation analysis of documents based on Citespace.

4. Conclusion

An overview of the research in the field of risk from ENMs was presented with the information related to annual publications, categories, journals, institutions, countries, funding sources, research emphases and tendencies. Researches on risk from ENMs increased sharply during 2003–2012. Many studies in the categories of environmental sciences, Toxicology, and Nanoscience & Nanotechnology have been taken to explore the toxicity and environmental risk. The United States, China, UK, Italy and Germany had high productivity in total articles. The Chinese Academy of Sciences took the leading position of the institutions in total publications. The synthesized analysis by co-citation and words from author keywords provided the clues for hot issues. It reveals that research in the field of risk from ENMs is roughly consisted of two aspects as follows: health effect and nanotoxicology, and environmental behavior and ecotoxicity. The number of publications per year has increased steadily since approximately 2006.

Table 6
Top 30 frequency of key words used.

Key words	TP	R (%)
Nanoparticles/nanoparticle	167	24.1
Nanomaterials/nanomaterial	156	22.5
Nanotoxicology	110	15.9
Nanotechnology	72	10.4
Nanotoxicity	65	9.4
Carbon nanotubes/carbon nanotube	63	9.1
Risk assessment	54	7.8
Cytotoxicity	47	6.8
Toxicity	39	5.6
Titanium dioxide/TiO_2	29	4.2
Ecotoxicity	25	3.6
Genotoxicity	23	3.3
Oxidative stress	21	3.0
Engineered nanomaterials	19	2.7
Fullerene/fullerenes	36	5.2
Aggregation	16	2.3
Exposure	16	2.3
Daphnia magna	14	2.0
EHS	14	2.0
Environment	14	2.0
Regulation	14	2.0
Risk management	14	2.0
Risk	13	1.9
Inflammation	12	1.7
Reactive oxygen species	12	1.7
Apoptosis	11	1.6
Exposure assessment	11	1.6
In vitro	11	1.6
Zebrafish	11	1.6
Ecotoxicology	10	1.4

TP: Total publication; R: Rank.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgments

This study was financially supported by the Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20120162110019), the National Natural Science Foundation of China (Grant No.21277175), and Shenzhen special fund for development of strategic emerging (Grant No. JCYJ20120618164317119). The authors would like to express their thanks to Li Li from Peking University for his critical reading of the manuscript. The authors also wish to thank Professor Yuh-Shan Ho Group for their helpful directing of bibliometric method.

References

Åkerman ME, Chan WCW, Laakkonen P, Bhatia SN, Ruoslahti E. Nanocrystal targeting in vivo. Proc Natl Acad Sci U S A 2002;99(20):12617–21.
Ashikaga T, Wada M, Kobayashi H, Mori M, Katsumura Y, Fukui H, et al. Effect of the photocatalytic activity of TiO_2 on plasmid DNA. Mutat Res 2000;466(1):1–7.
Braun T, Glanzel W, Grupp H. The scientometric weight of 50 nations in 27 science areas, 1989–1993. Part I. All fields combined, mathematics, engineering, chemistry and physics. Scientometrics 1995;33:263–93.

Chen C. Searching for intellectual turning points: progressive knowledge domain visualization. Proc Natl Acad Sci U S A 2004;101(Suppl. 1):5303–10.
Chen C. CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inf Sci Technol 2006;57(3):359–77.
Chen KL, Elimelech M. Aggregation and deposition kinetics of fullerene (C60) nanoparticles. Langmuir 2006;22(26):10994–1001.
Chen G, Walker SL. Role of solution chemistry and ion valence on the adhesion kinetics of groundwater and marine bacteria. Langmuir 2007;23(13):7162–9.
Chithrani BD, Ghazani AA, Chan WCW. Determining the size and shape dependence of gold nanoparticles uptake into mammalian cells. Nano Lett 2006;6:662–8.
Chiu WT, Ho YS. Bibliometric analysis of tsunami research. Scientometrics 2007;73(1):3–17.
Chiu WT, Huang JS, Ho YS. Bibliometric analysis of severe acute respiratory syndrome-related research in the beginning stage. Scientometrics 2004;61(1):69–77.
Colvin VL. The potential environmental impact of engineered nanomaterials. Nat Biotechnol 2003;21(10):1166–70.
Donaldson K, Aitken R, Tran L, Stone V, Duffin R, Forrest G, et al. Carbon nanotubes: a review of their properties in relation to pulmonary toxicology and workplace safety. Toxicol Sci 2006;92(1):5–22.
Fu HZ, Wang MH, Ho YS. Mapping of drinking water research: a bibliometric analysis of research output during 1992–2011. Sci Total Environ 2013;443:757–65.
Gottschalk F, Nowack B. The release of engineered nanomaterials to the environment. J Environ Monit 2011;13:1145–55.
Hassellöv M, Readman JW, Ranville JF, Tiede K. Nanoparticle analysis and characterization methodologies in environmental risk assessment of engineered nanoparticles. Ecotoxicology 2008;17(5):344–61.
Hirsch JE. An index to quantify an individual's scientific research output. Proc Natl Acad Sci U S A 2005;102(46):165–9.
Ho YS. Bibliometric analysis of biosorption technology in water treatment research from 1991 to 2004. Int J Environ Pollut 2008;34(1):1–13.
Ho YS, Satoh H, Lin SY. Japanese lung cancer research trends and performance in Science Citation Index. Intern Med 2010;49(20):2219–28.
Hullmann A. Measuring and assessing the development of nanotechnology. Scientometrics 2007;3(70):739–58.
Hyung H, Fortner JD, Hughes JB, Kim JH. Natural organic matter stabilizes carbon nanotubes in the aqueous phase. Environ Sci Technol 2007;41:179–84.
Keller AA, Wang H, Zhou D, Lenihan HS, Cherr G, Cardinale B, et al. Stability and aggregation of metal oxide nanoparticles in natural aqueous matrices. Environ Sci Technol 2010;44(6):1962–7.
Klaine SJ, Alvarez PJ, Batley GE, Fernandes TF, Handy RD, Lyon DY, et al. Nanomaterials in the environment: behavior, fate, bioavailability, and effects. Environ Toxicol Chem 2008;27(9):1825–51.
Klein S, Hage JJ. Measurement, calculation, and normal range of the ankle–arm index: a bibliometric analysis and recommendation for standardization. Ann Vasc Surg 2006;20(2):282–92.
Kreyling WG, Semmler M, Erbe F, Mayer P, Takenaka S, Schulz H, et al. Translocation of ultrafine insoluble iridium particles from lung epithelium to extrapulmonary organs is size dependent but very low. J Toxic Environ Health A 2002;65(20):1513–30.
Law CW, James JT, McCluskey R, Hunter R. Pulmonary toxicity of single-wall carbon nanotubes in mice 7 and 90 days after intratracheal instillation. Toxicol Sci 2004;1(77):126–34.
Lecoanet HF, Bottero JY, Wiesner MR. Laboratory assessment of the mobility of nanomaterials in porous media. Environ Sci Technol 2004;38(19):5164–9.
Li JF, Zhang YH, Wang XS, Ho YS. Bibliometric analysis of atmospheric simulation trends in meteorology and atmospheric science journals. Croat Chem Acta 2009a;82:695–705.
Li LL, Ding GH, Feng N, Wang MH, Ho YS. Global stem cell research trend: bibliometric analysis as a tool for mapping of trends from 1991 to 2006. Scientometrics 2009b;80(1):39–58.
Li J, Wang MH, Ho YS. Trends in research on global climate change: a Science Citation Index expanded-based analysis. Glob Planet Chang 2011;77(1):13–20.
Limbach LK, Li Y, Grass RN, Brunner T, Hintermann M, Muller M, et al. Oxide nanoparticles uptake in human lung fibroblasts: effects of particle size, agglomeration, and diffusion at low concentration. Environ Sci Technol 2005;39:9370–6.
Lin D, Xing B. Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. Environ Pollut 2007;150:243–50.
Lowry GV, Gregory KB, Apte SC, Lead JR. Transformations of nanomaterials in the environment. Environ Sci Technol 2012;46(13):6893–9.
Lyon DY, Adams LK, Falkner JC, Alvarez P. Antibacterial activity of fullerene water suspensions: effects of preparation method and particle size. Environ Sci Technol 2006;40(14):4360–6.
Maynard AD, Aitken RJ, Butz T, Colvin V, Donaldson K, Oberdorster G, et al. Safe handling of nanotechnology. Nature 2006;444:267–9.
Mela GS, Cimmino MA. An overview of rheumatological research in the European Union. Ann Rheum Dis 1998;57(11):643–7.
Mueller NC, Nowack B. Exposure modeling of engineered nanoparticles in the environment. Environ Sci Technol 2008;42(12):4447–53.
Nel A, Xia T, Madler L, Li N. Toxic potential of materials at the nanolevel. Science 2006;311:622–7.
Nowack B, Bucheli TD. Occurrence, behavior and effects of nanoparticles in the environment. Environ Pollut 2007;150(1):5–22.
Oberdorster E. Manufactured nanomaterials (Fullerenes, C_{60}) induce oxidative stress in the brain of juvenile largemouth bass. Environ Health Perspect 2004;112(10):1058–62.
Oberdoster G, Oberdoster E, Oberdorster J. Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. Environ Health Perspect 2005;7(113):823–39.
Owen R, Handy R. Formulating the problems for environmental risk assessment of nanomaterials. Environ Sci Technol 2007;41:5582–8.
Pan Y, Neuss S, Leifert A, Fischler M, Wen F, Simon U, et al. Size-dependent cytotoxicity of gold nanoparticles. Small 2007;3(11):1941–9.
Qin J. Semantic similarities between a keyword database and a controlled vocabulary database: an investigation in the antibiotic resistance literature. J Am Soc Inf Sci 2000;51(2):166–80.
Rejman J, Oberle V, Zuhorn I, Hoekstra D. Size-dependent internalization of particles via the pathways of clathrin-and caveolae-mediated endocytosis. Biochem J 2004;377:159–69.
Roco MC. Broader societal issues of nanotechnology. J Nanoparticle Res 2003;5:181–9.
Saleh N, Kim HJ, Phenrat T, Matyjaszewski K, Tilton R, Lowry G. Ionic strength and composition affect the mobility of surface-modified Fe0 nanoparticles in water-saturated sand columns. Environ Sci Technol 2008;42(9):3349–55.
Saleh NB, Pfefferle LD, Elimelech M. Influence of biomacromolecules and humic acid on the aggregation kinetics of single-walled carbon nanotubes. Environ Sci Technol 2010;44(7):2412–8.
Semmler M, Seitz J, Erbe F, Mayer P, Heyder J, Oberdörster G, et al. Long-term clearance kinetics of inhaled ultrafine insoluble iridium particles from the rat lung, including transient translocation into secondary organs. Inhal Toxicol 2004;16(6–7):453–9.
Service RF. Nanomaterials show signs of toxicity. Science 2003;300:243.
Tachikawa T, Asanoi Y, Kawai K, Tojo S, Sugimoto A, Fujitsuka M, et al. Photocatalytic cleavage of single TiO_2/DNA nanoconjugates. Chemistry 2007;14:1492–8.
Ugolini D, Cimmino MA, Casilli C, Mela GS. How the European Union writes about ophthalmology. Scientometrics 2001;52(1):45–58.
Wang XW, Liu D, Ding K, Wang XR. Science funding and research output: a study on 10 countries. Scientometrics 2012;91:591–9.
Warheit DB, Laurence BR, Reed KL, Roach D, Reynolds G, Webb T. Comparative pulmonary toxicity assessment of single-wall carbon nanotubes in rats. Toxicol Sci 2004;1(77):117–25.
Wiesner MR, Lowry GV, Alvarez P, Dionysiou D, Biswas P. Assessing the risks of manufactured nanomaterials. Environ Sci Technol 2006;40(14):4336–45.
Wu J, Liu W, Xue C, Zhou S, Lan F, Bi L, et al. Toxicity and penetration of TiO_2 nanoparticles in hairless mice and porcine skin after subchronic dermal exposure. Toxicol Lett 2009;191:1–8.
Xie SD, Zhang J, Ho YS. Assessment of world aerosol research trends by bibliometric analysis. Scientometrics 2008;77(1):113–30.
Yang HL, Xi ZG, Yan J, Zhang W. Ecological and environmental health effects of emerging contaminant of concern. Asian J Ecotoxicol 2009;4:28–34.
Zhang GF, Xie SD, Ho YS. A bibliometric analysis of world volatile organic compounds research trends. Scientometrics 2010;2(83):477–92.