Science of the Total Environment 441 (2012) 19–27

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

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

Review

Constructed wetlands, 1991–2011: A review of research development, current trends, and future directions

Wei Zhi, Guodong Ji *

Key Laboratory of Water and Sediment Sciences, Ministry of Education, Department of Environmental Engineering, Peking University, Beijing 100871, China

HIGHLIGHTS

► A bibliometric approach to evaluate global scientific constructed wetland(s) research.
► Assessed current and future directions using a SCI-EXPANDED database from 1991 to 2011.
► Qualitatively analyzed three keyword types: author keywords, title words, and KeyWords Plus.
► The dominant constructed wetlands research hotspots from 1991 to 2011 included water, nutrients, plants, and flow.
► "Phytoremediation" and "horizontal" are predicated to become the next primary research focuses in the upcoming years.

ARTICLE INFO

Article history:
Received 12 July 2012
Received in revised form 16 September 2012
Accepted 24 September 2012
Available online 4 November 2012

Keywords:
Constructed wetland
Research development
Current trend
Future direction
Bibliometric

ABSTRACT

This study explores a bibliometric approach to quantitatively evaluate global scientific constructed wetlands research, and statistically assess current trends, and future directions using the Science Citation Index Expanded (SCI-EXPANDED) database from 1991 to 2011. Articles referencing constructed wetlands were analyzed by accessing the following: publication language, output characteristics, publication performance by country and institution, author keywords, title words, and KeyWords Plus. Synthetically analyzing three keyword types, we concluded that the dominant constructed wetlands research hotspots from 1991 to 2011 included water, nutrients, plants, and flow. These four hotspots remained the most dominant research areas throughout our study period, and are predicted to remain the top research emphases in the near future. "Soil" also exhibited a notable increase since 2005, and is likely to become another notable area of research interest in the future. "Phytoremediation" and "horizontal" were not identified in 1991–1995, but exhibited marked increases from 136th (0.5%) and 169th (0.7%) in 1996–2000, to 9th (3.8%) and 11th (4.3%) in 2006–2011, respectively. Therefore, given the heightened attention during the last 15 years, these topics are likely to become a primary research focus in upcoming years.

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* Corresponding author. Tel.: +86 1062755914 87; fax: +86 1062756526.
E-mail address: jiguodong@pku.edu.cn (G. Ji).

0048-9697/$ – see front matter
http://dx.doi.org/10.1016/j.scitotenv.2012.09.064

1. Introduction

Constructed wetlands are artificially engineered ecosystems designed and constructed to manipulate biological processes, but do so within a semi-controlled natural environment (Ji et al., 2002; Vymazal, 2011). In wastewater treatment, a number of abiotic and biotic processes integral in wetland vegetation ecology, soil, and associated microbial assemblages assist in contaminant removal. Terms synonymous with "constructed wetlands" include "engineered wetlands", "artificial wetlands", "man-made wetlands", "treatment wetlands", and "reed beds". Generally, constructed wetlands can be classified according to different criteria: hydrology (surface-flow and subsurface-flow), macrophyte types (free-floating, emergent, and submerged), and flow path (horizontal or vertical) (Vymazal, 2011).

Two notable German researchers laid the foundation for constructed wetlands, Dr. Käthea Seidel in the 1960s, and Dr. Reinhold Kickuth in the 1970s. During the last five decades, constructed wetlands have evolved from empirical research into successful, increasingly more popular applications e.g., habitat restoration for native and migratory wildlife, anthropogenic discharge for wastewater, storm water runoff, sewage treatment, land reclamation following mining, refineries, and mitigation succeeding ecological disturbances, such as wetland loss due to land development projects. Constructed wetlands have been accepted as an attractive and economic alternative to a variety of pollution controls, including domestic wastewater (Konnerup et al., 2009), agricultural wastewater (Fink and Mitsch, 2004), industrial wastewater (Ji et al., 2007b), urban runoff water (Scholz and Hedmark, 2010), and acid mine drainage (Mitsch and Wise, 1998). Scientific publications on various aspects of constructed wetlands research have exhibited a marked increase in quantity over the last two decades, and a number of papers have been published in authoritative scientific journals, including Wetlands (Kayranli et al., 2010), Environmental Science and Technology (Budd et al., 2009), Water Research (Mitsch and Wise, 1998), and Ecological Engineering. Furthermore, constructed wetlands have received increasing attention and popularity from international scientists and engineers due to the economic and ecological benefits of these wetlands. First, compared to conventional energy-intensive treatment technologies (physical–chemical–biological treatments), constructed wetlands have been shown an attractive and stable alternative due to low costs, and energy savings (Zhang et al., 2009). Second, constructed wetlands provide potentially valuable wildlife habitat in urban and suburban areas (Rousseau et al., 2008), as well as esthetic value within the local natural environment. Finally, constructed wetlands can be beneficial in small to medium sized towns due to easy operation and maintenance, providing a useful complement to traditional sewage systems, which are used predominantly in large cities.

Numerous studies have been published on the various aspects of constructed wetlands, including insights on hydrological, physical, and biochemical processes. A growing number of scientific papers have been published that review the design, development, and performance of different types of constructed wetlands. However, to our knowledge, few attempts have been made to gather global systematic data, and conduct a large-scale review of the aspects of constructed wetlands scientific research. Consequently, several questions remain unclear. For example, over the last decade, what patterns in worldwide constructed wetlands research have emerged? Which country or institution has made the greatest contribution to constructed wetland development? More importantly, what are the current research emphases, and potentials for future research? The present study served to provide a global review of constructed wetlands research, using a bibliometric analysis focused on the above questions. Bibliometric analysis is a tool used to quantitatively and statistically conduct literature citation and content analyses. In terms of content, an analysis can glean patterns from scientific publications within a given topic, field, institution, or country (Ho, 2008). Furthermore, based on the Science Citation Index Expanded (SCI-EXPANDED), an online database, bibliometric methods can assess development trends or future research orientations using author keywords, title words, and KeyWords Plus (Li et al., 2009a, 2009b).

In this review, our objectives were to systematically evaluate conventional research, including document type, publication language, journal publication pattern, and country and institution publication performance/record. In addition, we applied an innovative methodology using predictive simulation models, and the analysis of author keywords, title words, and KeyWords Plus, to provide an overview, and identify areas of marked interest in constructed wetlands research.

2. Data sources and methodology

Data were derived from the Science Citation Index-Expanded (SCI-EXPANDED) database from the Institute for Scientific Information (ISI), a part of the Thompson Reuters Corporation. The Journal Citation Reports (JCR) Science 2011 edition maintains statistical citation data, and SCI indexes 8281 major science and technology journals, with citation references across 176 scientific disciplines. Since 1991, abstracts have been added to each SCI publication. Relevant information from a title, abstract, and keywords can be collected simultaneously in a topic search. Therefore, the online SCI-EXPANDED database, the Web of Science, was searched under the following keywords: "constructed wetland", "constructed wetlands", "engineered wetland", "engineered wetlands", "artificial wetland", "artificial wetlands", "man-made wetland", "man-made wetlands", "treatment wetland", "treatment wetlands", "reed bed", and "reed beds" for 1991 to 2011 to compile a bibliography of all papers related to constructed wetlands research.

Document information included author(s), title, source (journal title), language, document type, author keywords, addresses, cited reference count, times cited, publisher information, page count, ISSN, and subject category, among other source data. Full records were downloaded into Microsoft Excel 2007 for further analysis. The journal impact factor (IF) was obtained from JCR Science Edition 2011. Country and institution contributions were estimated by affiliation location of at least one author of the published paper. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified under a UK heading. Articles from Hong Kong (HK) and Taiwan (TW) were included in a China heading. Articles from French Guiana and Reunion were incorporated into a France heading. Collaboration type was determined by the author addresses, where the term "single country publication" was assigned if the researchers' addresses were from the same country. The term "internationally collaborative publication" was designated to articles that were coauthored by researchers from multiple countries. The term "single institution publication" was assigned if the researchers' addresses were from the same institution, and the term "inter-institutionally collaborative publication" was assigned to articles if the authors were from different institutions. The collaborative rate (CP%) was determined by the percentage of collaborative publications relative to total publications for each country or institute.

All articles associated with "constructed wetlands" during the past 21 years were analyzed based on the following comparative factors: document type and publication language; publication output characteristics i.e. total publications, number of authors, average number of authors per article, cited reference count, average number of references per article, page count, and average pages per journal article; publication patterns i.e. article number (percentage), impact factor (IF), journal subject category, and journal position by category; publication performance/record; and wetlands research interests determined by author keyword analysis, title words, and KeyWords Plus analyses.

3. Results and discussion

3.1. Document type and publication language

A total of 3787 publications, which met the selection criteria were obtained from the online version of SCI-EXPANDED, Web of Science. The document type distribution identified by ISI was analyzed. The 3787 publications related to constructed wetlands included 12 document types. Articles (2883) were the dominant document type, comprising 76% of the total publications, followed by articles and proceedings papers (678; 18%). All others represented small percentages as follows: reviews (140; 3.7%), meeting abstracts (34; 0.90%), editorial materials (16; 0.42%), news items (12; 0.32%), corrections (10; 0.26%), letters (9; 0.24%), notes (3; 0.080%), book chapters (2; 0.053%), reprints (1; 0.026%), and book reviews (1; 0.026%). On average, our search identified 21 articles per review, and 180 articles per editorial material. As journal articles represented the majority of document types that were also peer-reviewed within constructed wetlands research, the 2883 articles were subsequently used for further analyses.

Articles were published in 10 languages. English was the dominant language for articles published on constructed wetlands, and represented 99% of all articles. This may be an artifact of the fact that SCI is an American-based database, and most journals listed in ISI are published in English (Chiu and Ho, 2007). Furthermore, English is the official language of most international conferences and communications, and remains the dominant language in most fields (Chiu and Ho, 2007; Zhang et al., 2010). However, thirty eight non-English articles related to constructed wetlands were found in the SCI-EXPANDED database during the 1991 to 2011 period, including Portuguese (13; 0.34%), Spanish (12; 0.32%), German (8; 0.21%), French (7; 0.19%), Polish (4; 0.11%), Czech (3; 0.079%), Chinese (2; 0.053%), Russian (2; 0.053%), and Japanese (1; 0.026%).

3.2. Publication output characteristics

Abstract information is not available in the SCI-EXPANDED database prior to 1991, therefore "constructed wetland", "constructed wetlands", "engineered wetland", "engineered wetlands", "artificial wetland", "artificial wetlands", "man-made wetland", "man-made wetlands", "treatment wetland", "treatment wetlands", "reed bed", and "reed beds" were used as title search keywords to obtain a long-term publication output trend. Wallace and Knight (2006) indicated that the first documented use of a wetland within an engineered treatment vessel was by Cleophas Monjeau. The earliest article in the SCI-EXPANDED database that met our selection criteria was published in 1969. Fig. 1(a) shows that little research on constructed wetlands was conducted before 1990, and subsequently transitory fluctuations occurred from 1991 to 1995. The article number increased markedly in 1996, and exhibited a marked increase in 2005. Since the 1990s, exchange among scientists around the world facilitated constructed wetlands technology as an internationally preferred approach to deal with the diversity of issues associated with various wastewater types (Vymazal, 2011).

From 1991 to 2011, the article number increased from 21 in 1991 to 460 in 2011; and the difference in cumulative trends was evident between 1991 and 2000, and 2000 and 2011 (Fig. 1(b)). As a result, a power and exponential models were established to describe the relationships between the annual cumulative number of articles, and the year published for the two periods, respectively (Fig. 1(b)). A high correlation between article number and year was observed, with high coefficients of determination ($R^2 = 0.974$ for 1991–2000, and $R^2 = 0.998$ for 2000–2011). Power and exponential curve fitting results were respectively $C = 16.16Y^{1.289}$ and $C = 68.67e^{0.178Y}$, where C is the cumulative article number, and Y is the number of years since 1991. The exponential curve fitting indicated a high growth rate for articles published annually from 2000 to 2011. The exponential model predicted an increase in the number of future constructed wetlands articles published in 2015 and 2017, a respective double and triple that of the 2011 primary literature publications.

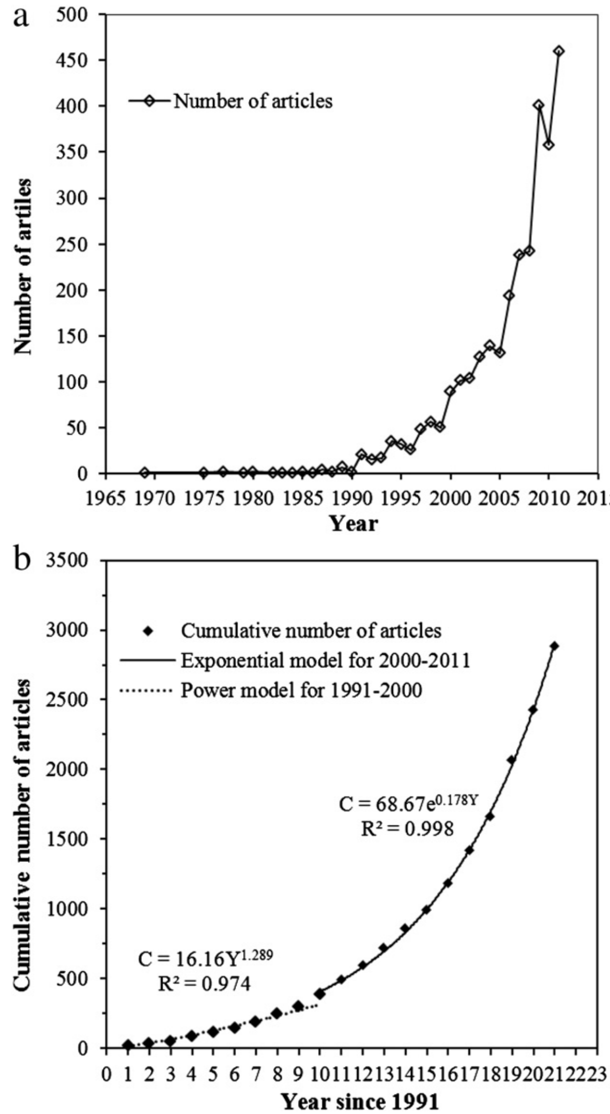

Fig. 1. Publication patterns and characteristics (a: the number of articles on constructed wetland(s) from 1969 to 2011; b: the relationship between the cumulative number of articles and year published, since 1991).

Publication characteristics from 1991 to 2011 are provided in Table S1. The annual article number (TP) increased considerably; 21 articles were published in 1991, with an increase to 460 in 2011. The total increase in average author number (AU), and references cited (NR) indicated a progressive growth of academic communication and collaboration in fields associated with constructed wetlands during the last 21 years. The average page number per article (PG/TP) fluctuated slightly, with an average length of 10 pages.

Results totaled 6453 authors from the 2883 articles analyzed. The maximum number of authors of one article was 22, and the most common number of authors was three, representing 721 (25%) papers. Two authors and four authors were responsible for 611 (21%) and 584 (20%) papers, respectively. One hundred and seventy-one (5.9%) articles were single authored. Among the 6453 authors, 4786 (74%) were credited in one article, followed by 862 (13%) in two, and 341 (5.3%) were cited in three articles. Subsequently, we established a model to describe the relationship between the author and number of articles published. Results detected a good correlation applying a power model: $X^{2.54}Y = 4300$ (Fig. 2(a)). A double logarithmic data plot depicted good linearity between author and article number, with a high coefficient of determination ($R^2 = 0.947$) in the range of one to 41 articles. Fig. 2(a) indicated that an adequate number of one or two-article researchers contributed a considerable amount (87%) to constructed wetlands research, and these researchers were highly likely to be expert in other academic areas other than constructed wetlands. This was in part due to a bridge between physical, chemical, and biological processes resulting in complex constructed wetlands research, and a need for diverse and multi-disciplinary knowledge, which required participation from many researchers in different disciplines. Furthermore, only 7.7% of all authors were credited in more than three articles. The diverse interests of researchers, which can decentralize their publications, and lower the number of articles on constructed wetlands research, might serve to explain these results. We predict that more researchers will be involved in constructed wetlands studies with the increased article publication rate as discussed above. Lotka's law describes authors' publication frequency, and the general Lotka model is described as: $X^nY = C$, where X is the number of articles, Y is the number of authors publishing X articles, n is an exponent, which is normally a value between 1.2 and 3.5, and C is a constant depending on the specific discipline. Thus, the articles in the field of constructed wetlands research from 1991–2011 conformed to Lotka's law with reliable results. Garcia and Scholz contributed the highest number of papers (41, 1.4%), followed by Zhao YQ (31, 1.1%). However, bias

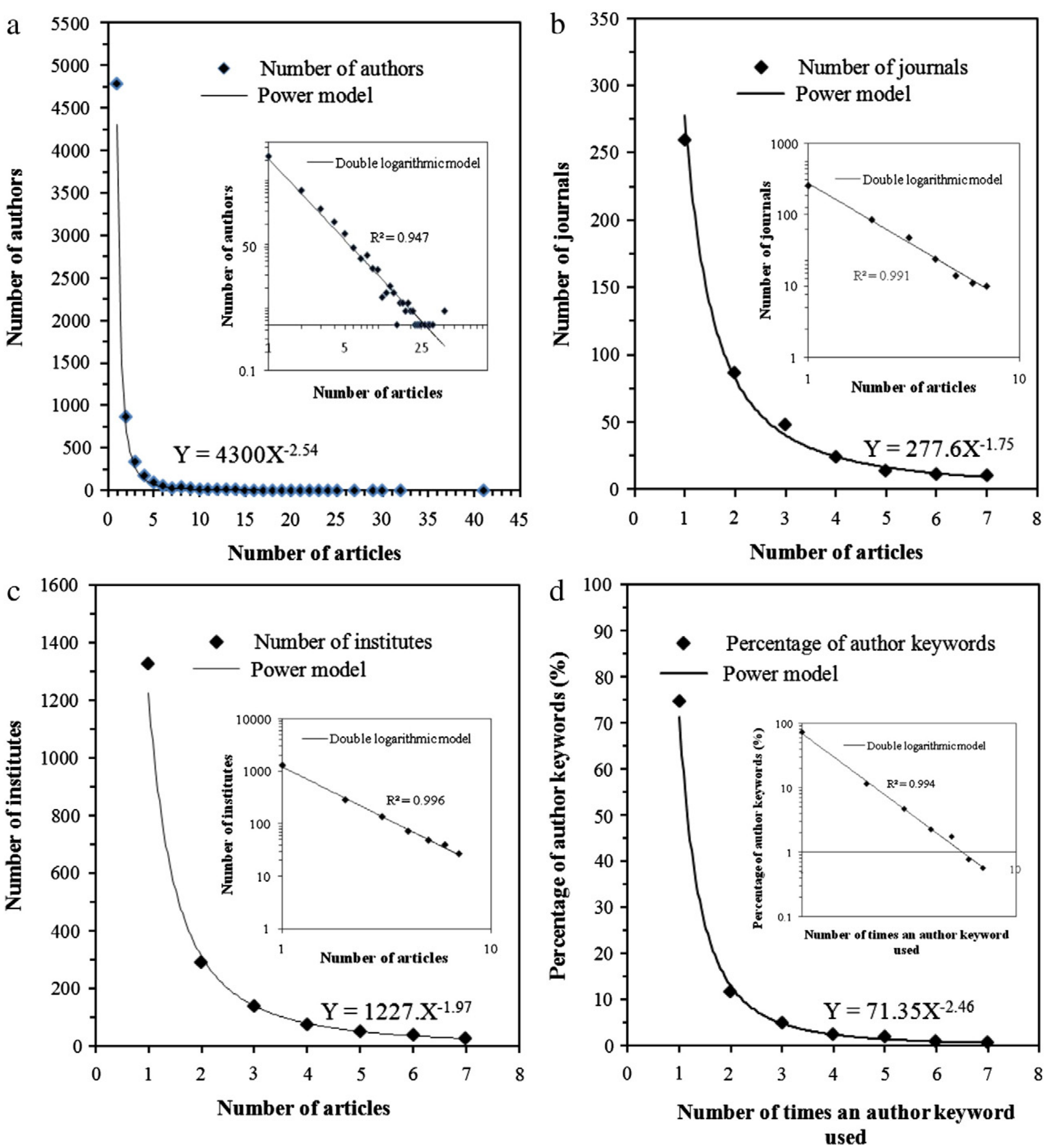

Fig. 2. Power models established to describe the relationship between a): the number of authors and their articles; b): the number of journals and their articles; c): the number of institutions and published articles; d): the percentage of total author keywords and the number of times the keyword was used.

would occur in this type of analysis for authors who consistently use the same name, and those that use different names in published works (Chiu and Ho, 2007). The rapid increase in published articles addressing constructed wetlands indicates the promise of more papers and researchers in the near future.

3.3. Journal publication patterns

The 2883 articles were published in 508 journals. Table S2 lists the 12 most productive journals, with the following data subdivisions: the article number (percentage), impact factor (IF), journal subject category, and journal position by categories. Results identified 12 journals responsible for 46% of the 2883 articles. Ecological Engineering ranked first in the number of published articles (432, 15%), followed by Water Research (158, 5.5%), and Water Science and Technology (125, 4.3%). A growth trend comparison among the top six productive journals showed total published article number exhibited overall growth from 1991 to 2011, with slight fluctuations from 2000 to 2005 (Fig. 3(a)). In recent years, Water Science and Technology and Bioresource Technology increased significantly, however Water Research showed a lower rate of increase.

In each of the 508 journals, 259 (51%) published one article investigating constructed wetlands research, and 86 (17%) journals published two articles. A high correlation between journal and article number was observed with the power model (Fig. 2(b)). A double logarithmic data plot showed good linearity between the journal and article number, with a high coefficient of determination ($R^2 = 0.991$) in the range of one to seven articles. Only a small percentage (11%) of the 508 journals published more than seven articles related to constructed wetlands research, and many articles were published in a broad array of academic journals (Fig. 2(b)). One possible explanation is that the interdisciplinary constructed wetlands studies are suitable for these journals, which usually have diverse subject areas and multidisciplinary scopes. Consequently, we predict that multidisciplines and varied subject areas will remain a characteristic trend of constructed wetlands studies in journal publications.

3.4. Country and institution publication performance

Seventeen articles lacking author address information were excluded from the total 2883 papers. Of the remaining 2866 articles representing 80 countries, 2369 (83%) were independent publications from the same country, and 497 (17%) were international collaborative publications coauthored by researchers from multiple countries. More than one third of the world's countries were involved in constructed wetlands research during the last 21 years, and Europe, North America, East Asia, and Oceania were the four dominant regions generating publications on constructed wetlands (Fig. 4). Table S3 lists the following: 20 most productive countries based on total publications; rank and share of single country publications; internationally collaborative publications; rank and share of first author and corresponding author publications; and number and percentage of internationally collaborative publications. Results indicated that the largest contributor was the USA with 949 (33%) total publications (Fig. 4, Table S3). China and the UK ranked second and third, with respective 396 (14%) and 252 (8.2%) total publications. Fig. 5 shows the relationship between the cumulative percentage of single country publications, and the top 20 most productive countries in single country publications. Results indicated that the 20 most productive countries were responsible for 85% of the single country publications. A logarithmic model was used to describe the relationship, and a good correlation was observed, with a high coefficient of determination ($R^2 = 0.997$) in the range of one to 20 countries (Fig. 5). Denmark exhibited the highest international collaborative rate (83%), followed by Germany (51%), the UK (46%), and Ireland (46%) (Table S3). In addition, the seven major industrialized countries (G7: Canada, France,

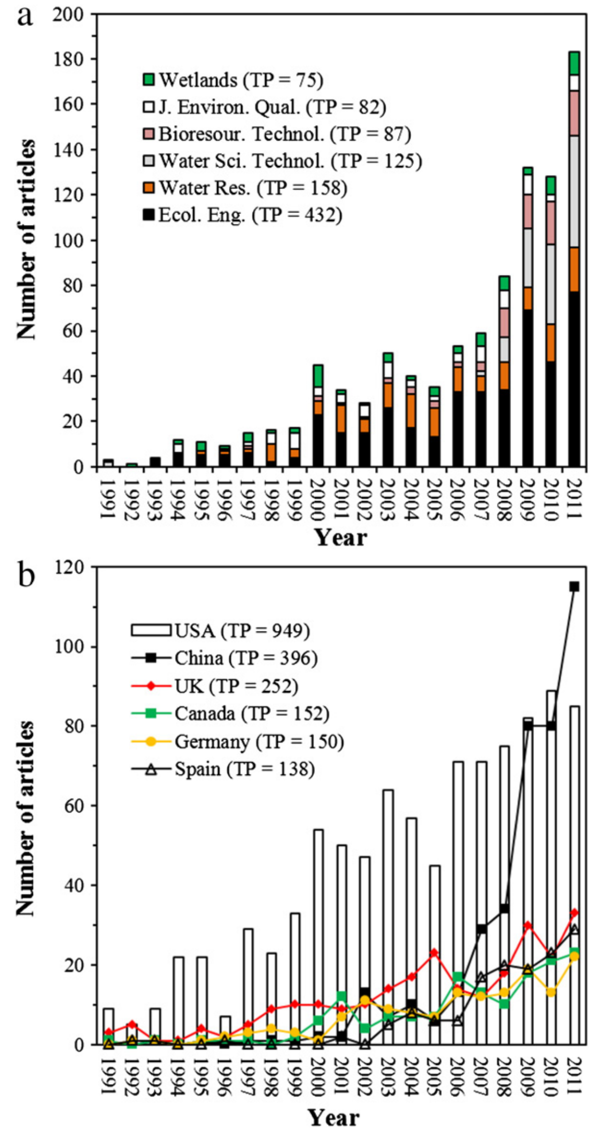

Fig. 3. Growth trends of the six most productive a): journals; b): countries.

Germany, Italy, Japan, the UK, and USA) were ranked in the top 12 for total publications, representing 60% of the total publications from 1991 to 2011. Furthermore, some developing countries (including China, Thailand, India, and Brazil) were listed in the 20 most productive countries. One possible explanation is that constructed wetlands are a cost-effective approach for wastewater treatment (Rousseau et al., 2008), and favored by developing countries.

Publication trend results for the six most productive countries (i.e. USA, China, the UK, Canada, Germany, and Spain) revealed the predominance of the USA in constructed wetlands research since 1991 (Fig. 3(b)). An overall increase in total article number for all six countries from 2000 to 2011 is likely due to the rapid development of constructed wetlands research throughout the world. Meanwhile, slight fluctuations in total article number from each country may be the result of a publication lag from the relatively long processes involved in constructed wetlands research. Compared with a stable growth rate for the USA, China and the UK exhibited notable growth in the last few years. China was close to the USA in 2009, and surpassed the USA by 35% in 2011. Therefore, China shows promise to lead the research papers in constructed wetlands in the following years. Rapid urbanization and industrialization, along with highly accelerated economic development in China have resulted in serious environmental problems. Traditional energy-intensive sanitation

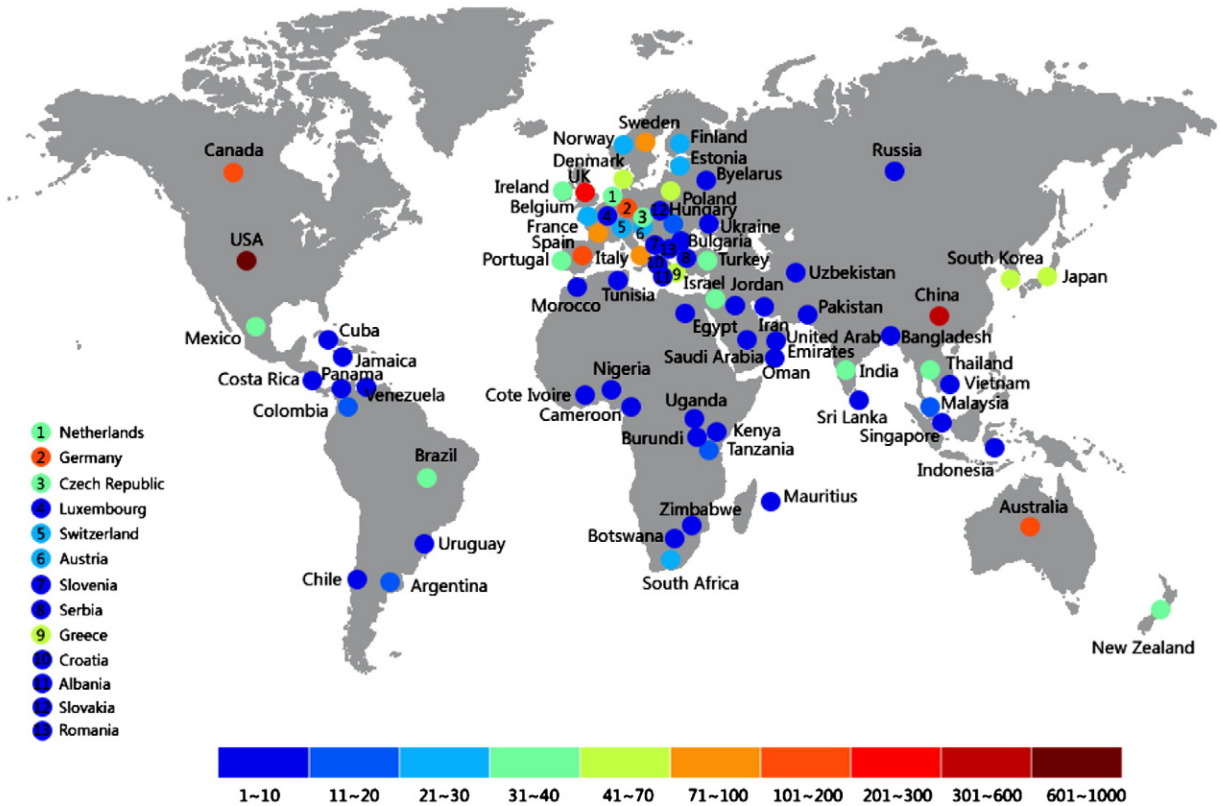

Fig. 4. Global SCI-derived map: total publications on constructed wetlands research over the 1991–2011 period.

systems have been limited, and not entirely effective to meet the country's needs, therefore wetland-related studies have been promoted (Zhang et al., 2009).

The 2866 articles represented 2063 institutions from 80 countries; 1269 (44%) articles were independent publications accomplished by one institution, and 1597 (56%) were inter-institutional collaborative publications coauthored by researchers from multiple institutions.

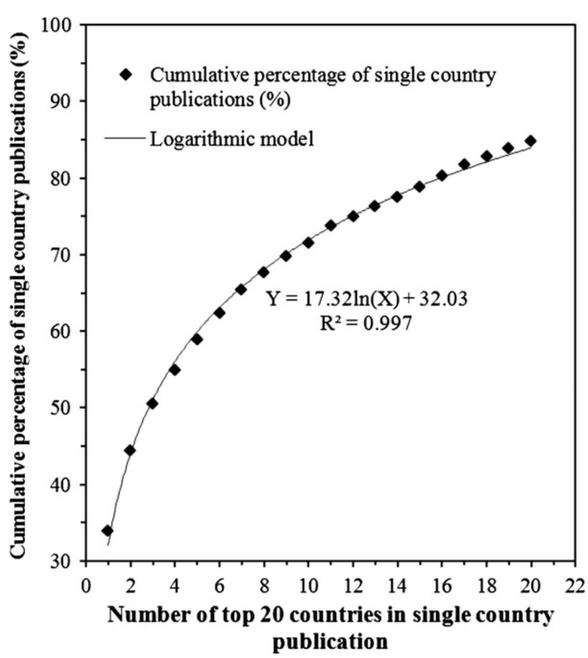

Fig. 5. The relationship between the cumulative percentage of single country publications and the top 20 countries in single country publications.

The 21 most productive institutions conducting research on constructed wetlands are provided in Table S4. Results indicated that the collaborative rate (CP%) among institutions was much higher than among countries (Tables S3 and S4). Twelve institutions in the USA, four in China, two in Spain, and one each in the UK, Ireland, and Estonia were ranked in the top 21 most productive institutions. The Chinese Academy of Sciences (76), United States Department of Agriculture—Agricultural Research Service (59), University of Florida (55), Louisiana State University (48), and Ohio State University (48) were the top five research institutions. It should be noted that the Chinese Academy of Sciences is an integrated research center with many independent branches throughout the country. We pooled the Academy branches under one heading for the study. Eighteen of the 21 institutions, with three exceptions (i.e. University College Dublin, South Florida Water Management District, and Wetlands Management Services), showed the most inter-institutional collaborative publications relative to single institutional publications. The United States Environmental Protection Agency held the highest collaborative rate (97%), followed by Consejo Superior de Investigaciones Científicas (CSIC, Spain), and Beijing Normal University (China) (91% and 91%, respectively). Collaboration and academic exchange play a substantial role in constructed wetlands research.

Among the 2063 institutions revealed in the search, 1326 (64%) institutions had only one article related to constructed wetlands research, 290 (14%) two articles, and 138 (6.7%) three articles. A high correlation between institution and article number was observed applying a power model (Fig. 2(c)). A double logarithmic data plot exhibited good linearity between institution and article number, with a high coefficient of determination ($R^2 = 0.996$) in the range of one to seven articles. The above analysis indicated that the majority (85%) of the 2063 institutions published no more than three articles related to constructed wetlands research during the last 21 years. It is highly likely that the number of institutions involved in constructed wetlands research will increase coincident with the number of articles, and there is no indication that the leading positions of the top 21institutions (Table S4) will be surpassed in the near future.

3.5. Research emphasis: author keywords, title words, and KeyWords Plus

Garfield (1990a,1990b) reported statistical analyses of keywords, and title word searches were successful to suggest future science directions. Bibliometric analysis using author keywords to analyze research trends and development has been demonstrated in recent years (Chiu and Ho, 2007). The article title, which calls for much deliberation from authors, should provide essential information regarding the entire paper to readers. In addition, "KeyWords Plus" has been generated independently of the author keywords as a supplement to describe paper contents, and contain increased depth and variety (Garfield, 1990a; Garfield, 1990b). For this reason, author keywords, title, and KeyWords Plus provide a reasonably detailed panorama of article theme and focus.

In terms of author keyword records, 2428 articles in the SCI-EXPANDED database were analyzed. A good correlation was observed using a power model to describe the relationship between the percentage of total author keywords, and the number of times an author keyword was used (Fig. 2(d)). A double logarithmic data plot demonstrated good linearity with a high coefficient of determination ($R^2 = 0.994$) in the range of one to seven times. Results showed that among the 5815 author keywords, only 8.3% of the total keywords were used more than three times (Fig. 2(d)). The large number of author keywords used less than three times might be related to discontinuity in the research, or a diverse research focus. In addition, the various uses of synonymous terms, spelling variations, and abbreviations might not be standard or widely accepted by researchers (Li et al., 2009a, 2009b). The top 20 author keywords for the study period are listed in Table 1, using 5-year intervals to guarantee a reasonable time-span, and minimize year-to-year fluctuations. Excluding "constructed wetlands", "constructed wetland", "wetlands", "wetland", "treatment wetlands", and "reed beds", which were the topic search keywords, "phosphorus" (180; 7.4%), "wastewater treatment" (151; 6.2%), "nitrogen" (139; 5.7%), and "wastewater" (7; 5.3%) were the four most frequently used author keywords (Table 1). During the entire study survey period, the ranking and percentage of "phosphorus" increased from 7th (6.4%) in the 1991–1995 date range to 3rd (7.6%) in the 2006–2011 period. "Nitrogen" ranked 12th in 1996–2000, increased to 6th in the 2001–2005 range, and 4th in 2006–2011. The ranking of "nutrients" ascended from 27th in the 1991–2000 period to 12th during the 2006–2011 period. Therefore, nutrient-related research remained vigorous throughout 1991–2011, and is predicted to remain a primary research emphasis in the near future, as nutrient removal is a key element in constructed wetlands technology (Garcia et al., 2010). In terms of wastewater, "wastewater treatment" and "domestic wastewater" were rarely identified in 1991–1995, but reached respectively 4th (9.5%) and 52nd (1.0%) in 1996–2000, and experienced a second rise to 3rd (8.7%) and 33rd (1.2%) in 2001–2005, respectively. "Wastewater" ranked 63rd (1.3%) in the 1991–1995 period, increased markedly to 5th (9.0%) in 1996–2000, decreased slightly to 7th (6.6%) in 2001–2005, and ranked 6th (4.6%) in 2006–2011. Based on the performance of these three author keywords related to water research, it is obvious that issues related to wastewater have become a primary focus since 1996. "Phytoremediation" ranked 136th (0.5%) in 1996–2000, and showed a significant increase to 21st (1.9%) in 2001–2005, and 9th (3.8%) during the 2006–2011 period. The increased use of "phytoremediation" in recent years indicated that phytoremediation has gradually been recognized as a cost-effective and environmentally safe option for remediation and restoration of polluted and degraded ecosystems among the scientific community (Garbisu and Alkorta, 2001; Schwitzguebel et al., 2011). Similarly,

Table 1
20 most used author keywords, 1991 to 2011.

Author keywords	TP	1991–2011 R (%)	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2011 R (%)
Constructed wetlands	479	1 (20)	1 (24)	1 (30)	1 (25)	2 (17)
Constructed wetland	387	2 (16)	3 (9.0)	3 (10)	2 (14)	1 (18)
Phosphorus	180	3 (7.4)	7 (6.4)	7 (6.5)	4 (7.3)	3 (7.6)
Wastewater treatment	151	4 (6.2)	N/A	4 (9.5)	3 (8.7)	5 (5.4)
Nitrogen	139	5 (5.7)	7 (6.4)	12 (4.5)	6 (7.1)	4 (5.5)
Wetlands	136	6 (5.6)	1 (24)	2 (12)	4 (7.3)	11 (3.5)
Wastewater	128	7 (5.3)	63 (1.3)	5 (9.0)	7 (6.6)	6 (4.6)
Wetland	113	8 (4.7)	63 (1.3)	8 (6.0)	8 (5.6)	7 (4.4)
Denitrification	103	9 (4.2)	12 (5.1)	6 (8.5)	11 (3.5)	8 (3.9)
Phragmites australis	91	10 (3.7)	63 (1.3)	8 (6.0)	9 (3.9)	10 (3.5)
Water quality	83	11 (3.4)	3 (9.0)	10 (5.5)	9 (3.9)	13 (2.8)
Phytoremediation	73	12 (3.0)	N/A	136 (0.5)	21 (1.9)	9 (3.8)
Nitrification	73	12 (3.0)	12 (5.1)	11 (5.0)	12 (3.1)	14 (2.6)
Nutrients	72	14 (3.0)	27 (2.6)	14 (3.5)	14 (2.9)	12 (2.9)
Nitrogen removal	58	15 (2.4)	63 (1.3)	18 (2.5)	16 (2.7)	17 (2.3)
Treatment wetlands	56	16 (2.3)	63 (1.3)	136 (0.50)	14 (2.9)	15 (2.4)
Heavy metals	54	17 (2.2)	N/A	52 (1.0)	17 (2.5)	15 (2.4)
Reed beds	54	17 (2.2)	12 (5.1)	14 (3.5)	17 (2.5)	21 (1.9)
Nutrient removal	52	19 (2.1)	12 (5.1)	16 (3.0)	19 (2.1)	20 (1.9)
Domestic wastewater	46	20 (1.9)	N/A	52 (1.0)	33 (1.2)	18 (2.3)

TP: total publications; R (%): rank and share of the author keyword; N/A: not available due to the reason that the author keyword did not appear in the study period.

the ranking "heavy metals" exhibited a progressive rise during the last 21 years, which indicated more attempts to remove heavy metals with constructed wetlands (Scholz, 2003; Yeh et al., 2009). However, "water quality" and "nutrient removal" descended from 3rd (9%) and 12th (5.1%) in 1991–1995, to 13th (2.8%) and 20th (1.9%) in 2006–2011, respectively. We attributed the ranking and word percentage declines to lower growth rates relative to other similar words.

A single word title analysis was also conducted. Individual words can be used to identify the authors' emphasis (Zhang et al., 2010). Prepositions, including "of" and "in", were frequently used in titles, however these words obviously had no utility in a research trend analysis. Therefore, "of," "to," "in," "and," "the," "a," "an," "for," "with," "by," "using," "high," and "more," among other similar words were excluded from the analysis. Based on 5-year categories, our analysis identified the 20 most frequently used single words in titles (Table 2). Excluding the search keywords "constructed," "wetland," and "wetlands", the top two most frequently used single title words were "wastewater" and "water", which were consistent with "wastewater treatment," "wastewater," and "domestic wastewater" from the author keywords analysis. "Wastewater," "water," "domestic," "agricultural," "drainage," "effluent," and "quality" (1339; 46%) were title words associated with water research, which we determined as an area of high research interest in constructed wetlands. "Flow" ranked 12th (4.2%) in 1991–1995, showed a rise to 6th (6.5%) in 1996–2000, and remained at 6th (9.3%) during the 2001–2005 and (13%) 2006–2011 time periods. The ranking and percentage of "subsurface" increased from 64th (1.7%) in 1991–1995 to 21st (2.9%) in 1996–2000, and further increased to 7th (7.5%) in the 2001–2005 period, then exhibited a slight drop to 9th (6.6%) in 2006–2011. Four title words were identified related to flow from the word analysis (707; 25%) (i.e. "flow," "subsurface," "vertical," and "horizontal"), suggesting that the significance of flow pattern was recognized by more researchers in recent years to achieve more effective nutrient (Vymazal, 2011) and heavy metal (Garcia et al., 2010) removal, and we predict that this will remain an area of increased research interest in the upcoming years. Moreover, three single words (523; 18%) (i.e., "phosphorus," "nitrogen," and "nutrient") correlated with wetland nutrients, fluctuated slightly during the last 21 years, and represented another stable component of constructed wetlands research. "Plants" ranked 33rd (2.5%) in 1991–1995, progressed to 27th

(2.5%) in the 1996–2000 period, reached 18th (3.0%) in 2001–2005, and remained at 18th (3.2%) during 2006–2011. Consequently, the increased use of "plants" in title words indicated that plants were more actively investigated and applied to remediate, treat, stabilize, and control contaminants; and increased attention was given to plant research in recent years, congruent with the above analysis for author keywords. The ranking and percentage of "reed" descended from 5th (10%) during 1991–1995 to 18th (3.2%) in 2006–2011. There are two possible explanations for this decrease. Some general words are replaced by more specific or definite words in article titles. "Reeds" might belong to this case, which was more often replaced by its Latin name "Phragmites australis" in recent years. Another possible explanation is that some words are substituted by other synonyms in article titles. For example, "reed beds" is a terminology originating in Europe during early constructed wetland development, and was replaced by the more standard or uniform words "constructed wetlands" as constructed wetlands technology was introduced to other parts of the world.

ISI generates KeyWords Plus, which are words or phrases that appear in the titles of an article's references, but do not necessarily appear in the article title. KeyWords Plus might be applied to articles that have no author keywords, or might include important terms not listed among the title, abstract, or author keywords (Zhang et al., 2010). KeyWords Plus was employed as an author keyword and title word analysis. KeyWords Plus analysis identified the 20 most frequently used keywords, and the rank and share in different time periods (Table 3). As a whole, the research trend revealed by Keywords Plus was consistent with the author keywords, and title words analyses. Table 3 suggested that Keywords Plus primarily emphasized water ("waste-water," "waste-water treatment," and "water"), nutrient ("nitrogen," "phosphorus," "denitrification"), and plant ("plants," "macrophytes," and "Phragmites australis"). "Heavy metal" was also revealed in the top 20 Keywords Plus author keywords. In addition, Keywords Plus indicated "performance" and "systems" as feature keywords; and "soil," "macrophytes," "accumulation," "design," "retention," and "soils" appeared exclusively in Keywords Plus.

We identified weaknesses in the three independent types of keyword analyses. The challenges in these analyses were overcome by combining author keywords, title words, and Keywords Plus, then synonymic single words and congeneric phrases were summed into categories. Consequently, the historical development and future directions of constructed wetlands research were analyzed with objectives of ascertaining a more complete understanding of the field's past and future progress. Based on the keywords and title words from Tables 1, 2, and 3, research trends and hotspots were summed into two categories: internal and external components. Internal components (within constructed wetlands) included "flow," "plant," "soil," "retention," "accumulation," and "design", which are all the basic elements related to constructed wetlands. External components included "nutrients," "water," and "heavy metals", all referring to the target objects treated by constructed wetlands. The components listed in Figs. 6(a) and 6(b) include the plural forms, abbreviations, and other transformations, as well as words with similar meanings. For example, the component "nutrients" in Fig. 6(b) includes "phosphorus," "nitrogen," "nitrogen removal," "nutrient," "nutrients," "nutrient removal," "denitrification," and "nitrification". Fig. 6(a) and (b) roughly summarizes research emphases and trends. The dominant areas of constructed wetlands research interests from 1991 to 2011 were water, nutrients, plants, and flow. Meanwhile, these four hotspots showed a stable growth trend (Figs. 6(a) and 6(b)), and are predicted to remain the prominent directions of constructed wetlands research in the near future. "Soil" also exhibited a notable increase since 2005, and has potential to become another research focus in the future. The growing awareness of the soil's integral role in removing phosphorus and heavy metals has lead to increased research in this area (Garcia et al., 2010) (Fig. 6(a)). The "soil" or medium in a constructed wetland has the potential to adsorb, and chemically precipitate phosphorus in its removal, and involves major physicochemical removal processes of heavy metals, including sedimentation and filtration; sorption; and precipitation and co-precipitation.

4. Conclusion

Based on 3787 publications obtained from the SCI-EXPANDED database, we conducted a bibliometric exploration to provide an overview of constructed wetlands research. A composite model describing publication patterns of constructed wetlands research since 1991 predicted that the number of articles published in 2015 and 2017 will be two and three times that in 2011. Four mathematical models were successfully established to describe the relationships between the number of authors/journals/institutions and the corresponding article, the

Table 2
20 most used single title words, 1991 to 2011.

Words in title	TP	1991–2011 R (%)	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2011 R (%)
Constructed	1214	1 (42)	2 (37)	1 (46)	1 (43)	1 (42)
Wetland	926	2 (32)	3 (19)	3 (31)	2 (34)	2 (32)
Wetlands	872	3 (30)	1 (41)	2 (34)	3 (31)	3 (29)
Wastewater	532	4 (18)	121 (0.83)	4 (16)	4 (19)	4 (20)
Water	342	5 (12)	19 (3.3)	5 (10)	5 (11)	5 (13)
Flow	324	6 (11)	12 (4.2)	6 (6.5)	6 (9.3)	6 (13)
Phosphorus	202	7 (7.0)	12 (4.2)	6 (6.5)	9 (5.8)	8 (7.6)
Nitrogen	199	8 (6.9)	7 (6.7)	11 (3.6)	8 (6.0)	7 (7.7)
Subsurface	180	9 (6.2)	64 (1.7)	21 (2.9)	7 (7.5)	9 (6.6)
Plant	126	10 (4.4)	121 (0.83)	11 (3.6)	9 (5.8)	12 (4.2)
Nutrient	122	11 (4.2)	12 (4.2)	11 (3.6)	13 (4.5)	12 (4.2)
Reed	120	12 (4.2)	5 (10)	8 (5.8)	11 (5.3)	18 (3.2)
Domestic	109	13 (3.8)	N/A	63 (1.8)	14 (4.3)	14 (4.1)
Vertical	104	14 (3.6)	N/A	63 (1.8)	169 (0.83)	10 (5.0)
Horizontal	99	15 (3.4)	N/A	169 (0.70)	25 (2.7)	11 (4.3)
Agricultural	94	16 (3.3)	19 (3.3)	10 (4.0)	16 (3.8)	21 (3.0)
Drainage	89	17 (3.1)	7 (6.7)	9 (4.7)	21 (2.8)	26 (2.7)
Effluent	89	17 (3.1)	64 (1.7)	21 (2.9)	12 (4.8)	27 (2.7)
Plants	88	19 (3.1)	33 (2.5)	27 (2.5)	18 (3.0)	18 (3.2)
Quality	84	20 (2.9)	N/A	27 (2.5)	25 (2.7)	17 (3.2)

TP: total publications; R (%): rank and share of the word in title; N/A: not available due to the reason that the word did not appear in title during the study period.

Table 3
20 most used KeyWords Plus, 1991 to 2011.

KeyWords Plus	TP	1991–2011 R (%)	1991–1995 R (%)	1996–2000 R (%)	2001–2005 R (%)	2006–2011 R (%)
Constructed wetlands	583	1 (22)	45 (1.5)	2 (11)	1 (26)	1 (23)
Removal	514	2 (19)	5 (7.5)	1 (14)	2 (17)	2 (21)
Waste-water	340	3 (13)	14 (4.5)	7 (7.1)	3 (11)	3 (14)
Waste-water treatment	303	4 (11)	1 (13)	8 (5.8)	11 (5.8)	4 (14)
Performance	264	5 (10)	N/A	51 (1.8)	13 (5.4)	5 (13)
Nitrogen	229	6 (8.6)	2 (10)	4 (8.8)	6 (7.2)	6 (9.0)
Water	222	7 (8.4)	2 (10)	3 (11)	4 (10)	10 (7.5)
Systems	195	8 (7.4)	9 (6.0)	8 (5.8)	5 (7.4)	8 (7.6)
Plants	190	9 (7.2)	9 (6.0)	11 (5.3)	7 (6.5)	7 (7.6)
Phosphorus	169	10 (6.4)	5 (7.5)	8 (5.8)	7 (6.5)	13 (6.4)
Denitrification	168	11 (6.3)	4 (9.0)	18 (3.5)	12 (5.6)	11 (6.8)
Soil	161	12 (6.1)	N/A	17 (4.0)	9 (5.9)	12 (6.6)
Constructed wetland	151	13 (5.7)	N/A	N/A	31 (2.6)	9 (7.5)
Macrophytes	136	14 (5.1)	22 (3)	24 (3.1)	9 (5.9)	15 (5.2)
Accumulation	123	15 (4.6)	45 (1.5)	51 (1.8)	27 (3.0)	14 (5.6)
Design	117	16 (4.4)	N/A	11 (5.3)	21 (3.3)	17 (4.8)
Retention	112	17 (4.2)	14 (4.5)	13 (4.9)	17 (3.7)	20 (4.3)
Heavy-metals	111	18 (4.2)	45 (1.5)	18 (3.5)	42 (2.0)	16 (5.0)
Phragmites-australis	109	19 (4.1)	9 (6.0)	30 (2.7)	32 (2.4)	18 (4.7)
Soils	108	20 (4.1)	14 (4.5)	18 (3.5)	13 (5.4)	27 (3.7)

TP: total publications; R (%): rank and share of the KeyWords Plus; N/A: not available due to the reason that the KeyWords Plus did not appear in the study period.

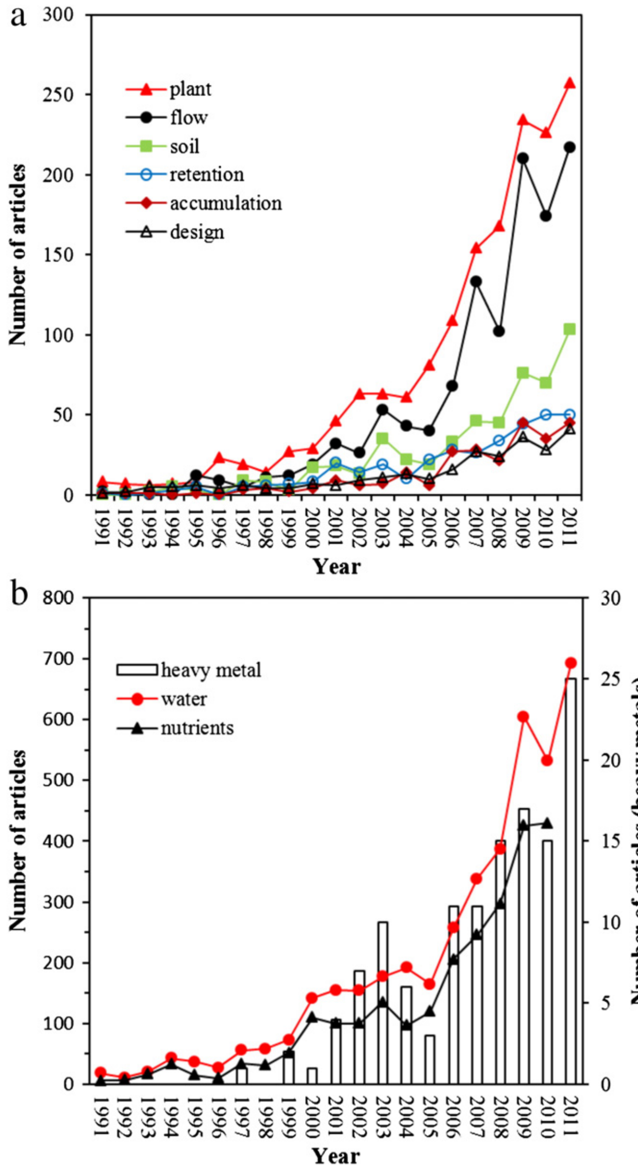

Fig. 6. Growth trends of a): internal components, including plant, flow, soil, retention, accumulation, and design; b): external components, including water, nutrients, and heavy metals.

percentage of total author keywords, and the number of times the keyword was used. In addition, the articles in the field of constructed wetlands research from 1991 to 2011 were found to conform to Lotka's law with reliable results. The USA exhibited predominance in constructed wetlands research since 1991, while China exhibited notable growth in the last decade, and shows promise to lead constructed wetlands research papers in upcoming years. The Chinese Academy of Sciences (76), United States Department of Agriculture-Agricultural Research Service (59), and University of Florida (55) were the top three research institutions. In this study, we synthetically analyzed the distribution and frequency of author keywords, title words, and KeyWords Plus; and described the development of constructed wetlands research during the last two decades, and predicted future research directions. The dominant areas of constructed wetlands research interest during the study period included water, nutrients, plants, and flow. These four topic hotspots remained vigorous throughout 1991–2011, and are predicted to remain the top research emphases in the near future. In addition, "soil" exhibited a notable increase since 2005, and has the potential to become another research hotspot in the future. "Phytoremediation" did not appear in author keywords during the period 1991–1995, while it exhibited a marked increase from 136th (0.5%) in 1996–2000 to 9th (3.8%) in 2006–2011. Similarly, "horizontal" was not found in title words in 1991–1995, but showed a substantial increase from 169th (0.7%) in 1996–2000 to 11th (4.3%) in 2006–2011. The changes in "phytoremediation" and "horizontal" were congruent with the increasing attention in the literature, and these topics are likely to become a primary research focus in upcoming years.

Acknowledgments

The National Natural Science Foundation of China (No. 51179001), the National Key Technology R&D Program of China (No. 2012BAJ25B01), and Fok Ying Tung Education Foundation (No. 122041) supported this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2012.09.064.

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