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Global trends and performances of publication on sewage sludge from 1991 to 2012

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Abstract

This study is a bibliometric analysis of sewage sludge researches to quantitatively and visually evaluate the global publication trends and research emphases using the Science Citation Index Expanded (SCI-Expanded) database from 1991 to 2012. Both “evaluative bibliometrics” and social network analysis methods were used to analyze the following aspects: publication characteristics, publication performances and collaborations of countries/territories and research emphases on author keywords, words in title and hotspots. An evaluating indicator, a-index, was applied to value the journals. The most productive country were USA, while the most productive journal was *Bioresour Technol*. Based on the network analyses of author keywords and words in title and the analysis of hotspots, “compost” and “anaerobic digestion” were the most popular disposal and treatment methods. “Heavy metals” were the contaminants with the greatest concerns. “Organic matters” such as “PPCPs” (abbreviation of pharmaceuticals and personal care products) and “PBDEs” (abbreviation of polybrominated biphenyl ethers) attracted comprehensive attention in recent years. “Soil” owned the most intimate relationship with sewage sludge due to its frequent appearance in titles and abstracts as an important approach for sewage sludge disposal.

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1 Introduction

Sewage sludge is the solid, semisolid, or liquid organic material that results from the treatment of domestic

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wastewater by municipal wastewater treatment plants (WWTPs). The wastewater contains domestic wastewater alone or with industrial wastewater and run-off from various sources that must be treated prior to municipal sewers^{1,2}. With WWTPs springing up in many countries, sewage sludge has become a particularly important problem all over the world. The annual production (dry-weight basis) of sewage sludge in European Union increased from some 5.5 Million tonnes per year (Mton/year) in 1992 to more than 10 Mton/year in 2010³. Annual production (dry-weight basis) in United States (USA) reached nearly 8 Mton/year⁴ and that in China came to 9 Mton/year in 2010⁵. Contaminants like heavy metals, organic pollutants and pathogens in wastewater are concentrated in sewage sludge through wastewater treatment process, which threaten environment and human health. Sewage sludge possesses high contents of moisture and organics depending on the original pollution load of wastewater, making it difficult for the sewage sludge to be treated or disposed of^{1,6,7}. In recent years, many researchers have been attracted to this field.

Since Hering⁸ and Winslow⁹ published the first two sewage sludge research articles on American Journal of Public Health in 1912, nearly 1,000 publications have been published on various aspects of sewage sludge, such as landspreading⁶, composting¹⁰, incineration¹¹ and landfilling¹². However, no systematic analysis of the scientific research on sewage sludge has been carried out to date. A common systematic research instrument, bibliometric method, has already been applied to measure scientific trends in many themes of science and engineering, including solid waste¹³, risk assessment¹⁴, *Helicobacter pylori*¹⁵, Meta-analysis in psychology¹⁶. Furthermore, the Science databases in Thomson Reuters Web, especially Science Citation Index Expanded (SCI-Expanded), have been widely used to analyze research performances from an international perspective¹⁷. Since Narin et al.¹⁸ first proposed the concept “evaluative bibliometrics”, many publications about the evaluation of the research trends through countries, and journals of a group of publications have been reported^{19,20}.

In addition, network analysis was introduced into bibliometric research in recent years and was used to indicate the research trends. Ding et al.²¹ employed co-word analysis to reveal patterns and trends in information retrieval field during the period of 1987 – 1997. Lee and Su²² used research focus parallelship network, keyword co-occurrence network and a two-dimensional knowledge map to understand the knowledge structure of electrical conducting polymer nanocomposite field. Zhu and Guan²³ applied small world complex network proposed by Watts and Strogatz²⁴ to analyze research in service innovation field.

Both “evaluative bibliometrics” and network analysis were applied to evaluate not only publication characteristics including document type, publishing trend, journal, publication performances and collaborations including country level, but also research emphases including author keywords, words in title and hotspots. Network analysis was first used to analyze words co-occurrence in title replenishing the analysis of author keywords co-occurrence network to obtain hotspots in the sewage sludge field.

2 Material and methods

2.1 Data collection

Data in the present study were based on the online version of the Science Citation Index Expanded (SCI Expanded), the Thomson Reuters Web of Science. In order to retrieve the publications in the subject of sewage sludge, the search was performed in topic field (including title, abstract, author keywords and keywords plus) and used keywords “sewage sludge*” and “biosolid*”. Biosolid was often used as an interchangeable term of sewage sludge in USA or a term to describe sewage sludge that has had additional processing for land application in other situation². Documents were restricted from 1991 to 2012, for abstracts have been added to each publication in SCI Expanded Since 1991.

A total of 13156 publications were initially retrieved. However, keywords plus were significant keywords from cited-by papers assigned to the source documents²⁵⁻²⁷, which means that publications in which the keywords “sewage sludge*” or “biosolid*” only appeared in the keywords plus field (n = 4187) were not closely related to the subject. To be accurate, this study removed these publications and focused on publications where retrieve keywords appeared in titles, abstracts or author keywords¹⁶.

2.2 Data analysis

Statistics were used to study the publication performances and research emphases, including the following comparative factors: document type and journal; countries/territories performances and collaborations; research emphases analyses by author keywords, words in titles and hotspots. The number of citations for each publication from the time it was published to March 2013 was obtained from the Thomson Reuters Web of Science online database, while the journal impact factor (IF) was acquired from JCR Science Edition 2013. Country contributions were estimated by addresses of at least one author of the paper. Articles from England, Scotland, Wales and North Ireland were assembled under United Kingdom (UK) heading; articles from Hong Kong published before 1997 were changed to China heading.

The h-index, proposed by Hirsch²⁸, defined as the number of total publications with citation number $\geq h$. It was widely used to evaluate researchers' academic achievements, but it fails in comparing the researchers with different research span. To remedy this limitation, a-index²⁹ was used in this study, which was derived from h-index to measure the influence of journals. The a-index (aI) was defined by the quotient between h-index (hI) and years since the journal published its first sewage sludge paper (t): $aI = hI/t$.

This study used social network to visualize results. Before employment of social network, we revised some words in author keywords and titles, because they were expressed in different forms with the same meaning. For example:

- Sewage sludge, sewage sludges, and sewage-sludge were standardized to sewage sludge;
- Modelling and modeling were standardized to modeling;
- Compost, composts and composting were standardized to compost;
- POPs, POP and persistent organic pollutants were standardized to POPs;
- Zn and zinc were standardized to Zn.

Three types of social networks were generated in this study, which were country collaboration network, author keywords co-occurrence network and title words co-occurrence network, respectively. In the country collaboration network, if two countries cooperated in publishing one or more articles, they would be linked together; likewise in the author keywords co-occurrence network, if two keywords co-occurred in at least one paper, they would be linked together.

In the social network, degree, weight, diameter, clustering coefficient and k-core are the common characteristics²³. Degree and weight are the simplest and most fundamental indexes, focusing on describing node property, while other indexes emphasize the characteristics of the whole network. Accordingly, degree and weight were chosen as the indicators in this paper. The degree of the node is defined as the number of neighbors it has. For example, in the country collaboration network, if country A had collaborated with 15 other countries, its degree was 15. The larger the degree is, the more information the node can spread to others, and the more important the node is in the network. The other indicator applied in the study is the weight of two connected nodes. The weight of two connected nodes is defined as the times they have linked. The larger weight means the closer connection. For instance, in the author keywords co-occurrence network, if keyword B and C had co-occurred in 15 papers, their weight was 15. The degree and weight were defined as follows:

$$D(i) = \sum_i m_{ij} \quad (1)$$

If node i and node j are linked, $m_{ij} = 1$.

$$W(ij) = \sum n_{ijk} \quad (2)$$

If node i and node j are together in paper k , $n_{ijk} = 1$; or $n_{ijk} = 0$. N is the total number of papers.

3 Results and discussion

3.1 Document type and publication characteristics

Among all the 8969 publications related to sewage sludge in titles, abstracts and author keywords fields during the 22-year study period, 69% (6222 publications) were retrieved by "sewage sludge*", with other 31% (2747)

searched by “biosolid*”, 44% of which were published by USA. Moreover, in this study, 14 document types were found in these 8969 publications. Article (7233) was the dominant document type accounting for 81% of the total publications, followed by proceedings paper (1037, 12%), review (267, 3.0%), news item (145, 1.6%) and meeting abstract (112, 1.2%). Others were less than one hundred in total showing less significance, including editorial material (65), letter (35), note (30), correction (26), book chapter (6), reprint (5), discussion (4), addition (3) and software review (1).

Because articles represented the majority of the total publications and most of them were original works, further analyses were focused on the articles (7233). From 1991 to 2012, total publication number increased rapidly from 177 to 713, as shown in Fig. 1. Meanwhile, the number of articles had a steady growth from 148 to 667. An exponential model was established to confirm this stable increase. The exponential fitting curve was $APN = 118e^{0.0783(Y-1990)}$, where APN is the annual publication number of articles and Y is the number of publication year. In addition, a good correlation between the annual publication number of articles and number of year was observed with a large coefficient of determination ($R^2 = 0.977$).

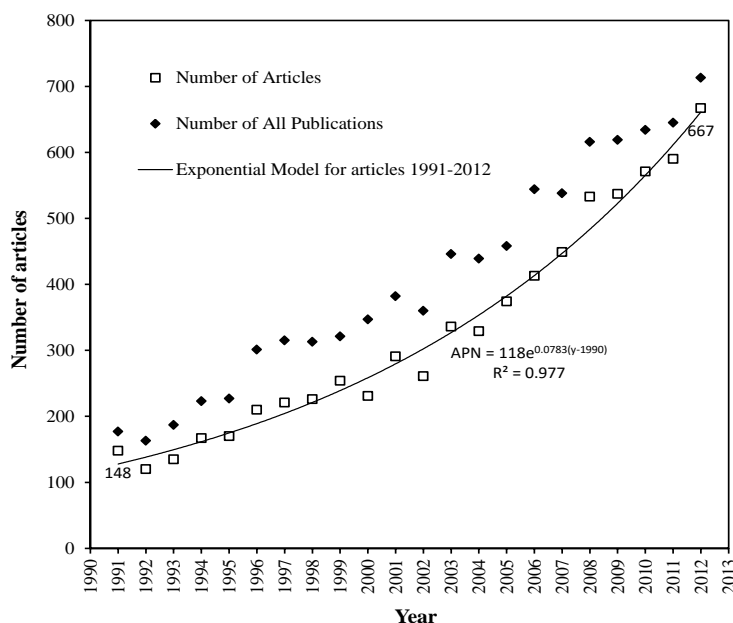


Fig. 1. Number of all publications and articles on sewage sludge, 1991 – 2012.

3.2 Journals

Articles (7233) were published in a total of 844 journals, though 364 journals (43%) only published one article about sewage sludge research. On the contrary, 14 most notable journals published over 32% of all the articles. The most productive journal was *Bioresource Technology* (285, 3.9%), followed by *Chemosphere* (275, 3.8%), *Journal of Environmental Quality* (269, 3.7%), *Water Research* (209, 2.9%) and *Environmental Science & Technology* (173, 2.4%). *Biocycle* had once been a productive journal before it suspended publication at 2003. Among the top 14 most productive journals, *Journal of Environmental Quality* owned the highest aI ($aI = 2.2$), and became the most influential journal in the sewage sludge field, followed by *Environmental Science & Technology* ($aI = 2.1$). Except for *Journal of Environmental Quality*, a significant correlation was observed between the aI and the IF2012 of the rest 12 journals ($R^2 = 0.86$), indicating that the citation of articles of sewage sludge research made a high contribution to the impact factor of the journal¹⁶. *Journal of Environmental Quality* had a higher aI/IF2012 ratio (0.93) than other journals, indicating that articles related to sewage sludge published on *Journal of Environmental Quality* contributed more to the impact factor of this journal compared with other journals.

3.3 Countries/territories performances and collaborations

The contribution of different countries/territories was estimated by location of the affiliation of at least one author of the published papers. Excluding 109 articles lack of author address information, the remaining 7124 articles were from 100 countries. One third of the countries just published one or two paper, while the top 10 countries published 78% of the total articles. Two North American countries, five European countries, two Asian countries and one South American country (Brazil) ranked in the top 10 list (Table 1). USA with 1570 (22%) articles became the largest contributor, followed by Spain (829, 12%), UK (608, 8.5%) and China (550, 7.7%).

Table 1. Top 10 most productive countries, 1991 – 2012

Rank	Country	TP (%)	SP (R)	CP (R)	FP (R)	RP (R)	Degree
1	USA	1570 (22)	1262 (1)	308 (1)	1403 (1)	1332 (1)	51
2	Spain	829 (12)	654 (2)	175 (3)	719 (2)	737 (2)	36
3	UK	608 (8.5)	432 (3)	176 (2)	538 (3)	443 (4)	36
4	China	550 (7.7)	401 (4)	149 (4)	457 (4)	482 (3)	29
5	Germany	420 (5.9)	275 (7)	145 (5)	357 (6)	288 (7)	41
6	Canada	410 (5.8)	306 (6)	104 (7)	363 (5)	317 (6)	34
7	Poland	342 (4.8)	317 (5)	25 (23)	326 (7)	328 (5)	14
8	France	305 (4.3)	199 (9)	106 (6)	257 (8)	234 (9)	34
9	Brazil	265 (3.7)	229 (8)	36 (17)	241 (9)	249 (8)	11
10	Japan	257 (3.6)	178 (10)	79 (10)	215 (10)	211 (10)	24

TP (%): total publications of the countries and their percentages; SP (R), CP (R), FA (R), RP (R): single country publications, internationally collaborative publications, first author publications, and corresponding author publications of the countries and their ranks respectively; Degree: the degree of the countries in country collaboration network.

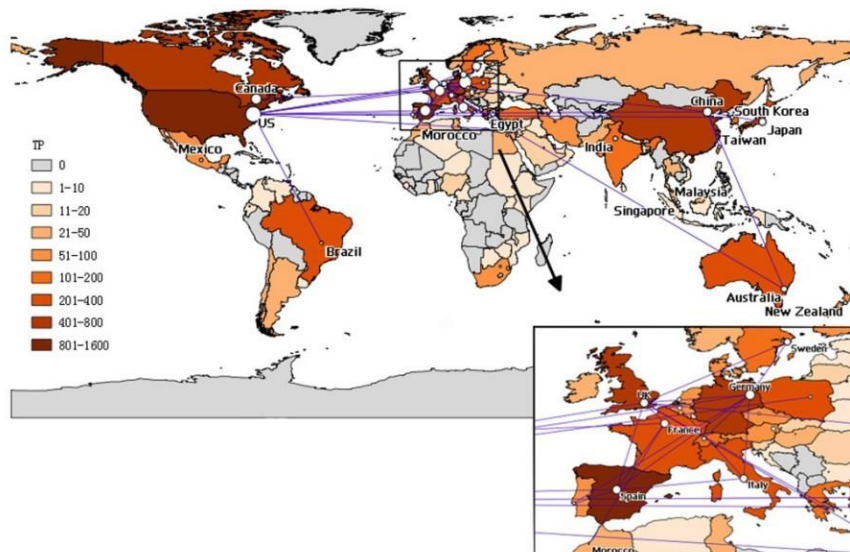


Fig. 2. Country performances and collaboration map, 1991 – 2012. The degree of each country and the weight of linked countries are both no less than 10. The size of the node’s symbol depends on the degree.

Among 7124 articles with author addresses from 100 countries/territories, 6019 (84%) were country independent publications and 1105 (16%) were international collaborative publications which increased from 5.5% of the total publications in 1991 to 20% in 2012. Figure 2 showed the worldwide publication situation and the collaboration in the sewage sludge field. Countries collaborated with at least ten other countries were marked, and the node size represented the degree in the country collaboration network. USA, Germany, Spain, UK, Canada, France and Italy were the countries with the most collaborators, illustrating that North America and Europe were in the center of the country collaboration network in the sewage sludge research field. Countries had collaborated with each other at least ten times were linked in Fig. 2. The results revealed that close communications were also mainly present in North America and Europe. Besides, China was the core of Asia in the network, closely contacting with USA, Japan, Taiwan, Australia and UK. For the African countries, only Morocco cooperated with France for fifteen times.

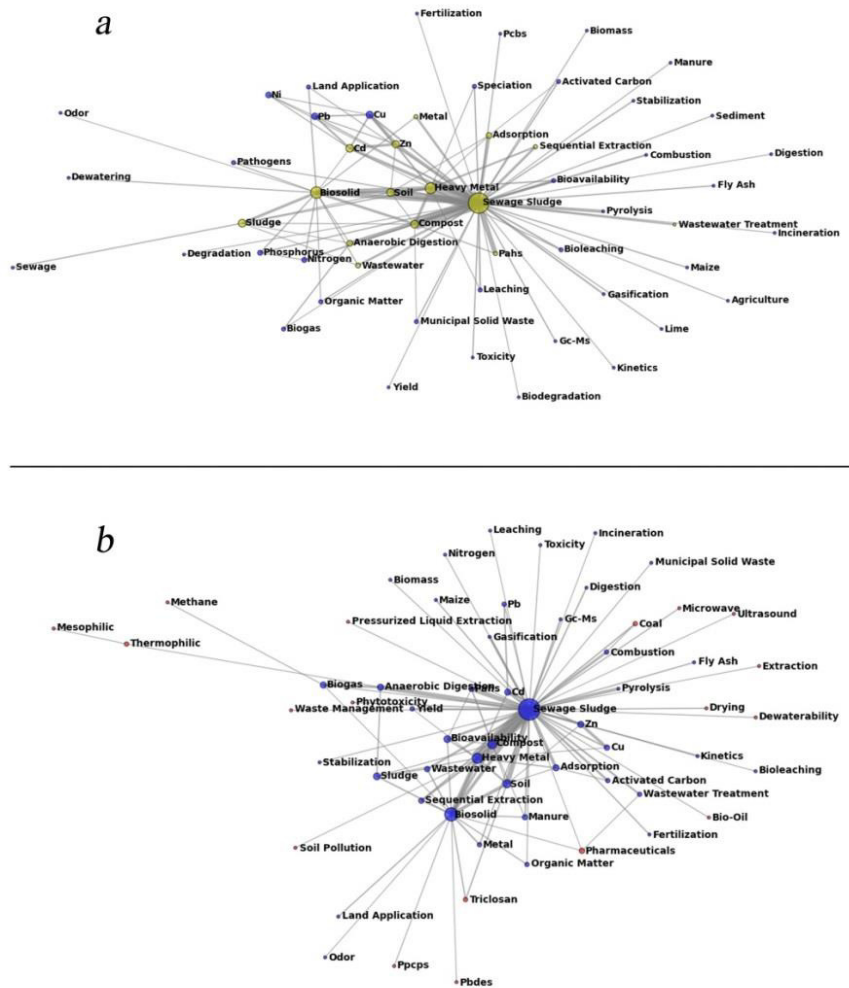


Fig. 3. The pop author keywords co-occurrence network a) in 1991 – 2012; b) in 2008 – 2012. The weight of linked keywords is larger than 15 in 3a and 7 in 3b. The size of the node's symbol depends on the degree, and the size of the line denotes their weight. The top 15 keywords in total during 1991 to 2012 are yellow in 3a, and the new keywords only appear in 3b are red.

3.4 Research emphases: author keywords, words in title and hotspots

3.4.1 Author keywords analysis

Articles with records of author keywords in the SCI database (5165) were analyzed. Among the 10169 keywords listed by authors, 73% (7430) were used only once, 12% (1249) twice and 4.6% (471) three times, which indicated the diversity of research focus and lack of continuity and coherence in the sewage sludge field^{13,30}. For instance, there were six ways to express the same meaning of sewage sludge as following: “sewage sludge(s)”, “sewage-sludge”, “wastewater sewage sludge”, “municipal sewage sludge” and “urban sewage sludge”, let alone keywords related to sewage sludge. Meanwhile, only 3.0% (304) of the author keywords were used no less than 10 times, representing the mainstream research topics related to sewage sludge. Excluding keywords “sewage sludge” and “biosolid”, which were the topic searching keywords, “heavy metal” (592, 11%), “compost” (369, 7.2%), “sludge” (288, 5.6%), “soil” (246, 4.8%) and “anaerobic digestion” (164, 3.2%) were the top five frequently used author keywords, followed by “Cd”, “adsorption”, “wastewater”, “PAHs” (abbreviation of polycyclic aromatic hydrocarbons), “Zn”, “wastewater treatment”, “metal”, “Cu”, “bioavailability” and “sequential extraction”.

To intuitively analyze author keywords, co-occurrence network was applied to show hotspots and their relations. The results of the pop author keywords co-occurrence network analyses both in the 22-year range and in the last five years were shown in Fig. 3, which was generated by keywords with the weight no less than 15 in the 22-year range and no less than 7 in the last five years. Keywords from the same paper were linked together, the node size represented the degree of the keywords and the size of the line was proportional to the co-occurrence time. Diverse keywords were found in the pop author keywords co-occurrence network, illustrating the popular topics in the sewage sludge research field. Source of sewage sludge like “wastewater” and “wastewater treatment”; similar research objects (solid or semisolid contaminative materials) like “municipal solid waste” and “sediment”; disposal and treatment methods like “stabilization”, “pyrolysis”, “land application”, “soil”, “incineration” and “compost”; research approaches of sewage sludge like “GC-MS”; pollutants in sewage sludge threatening the environment like “heavy metal”, “organic matter” and “pathogens” composed the majority of the pop author keywords co-occurrence network. “Sewage sludge” and “biosolid” were the cores of these two networks (Fig. 3). Heavy metals (including “Cd”, “Zn”, “Cu”, “Pb” and “Ni”) have long been popular since 1991. Some Organic matters, like “PCBs” (abbreviation of polychlorinated biphenyls) and “PAHs” were research hotspots during the 22-year period, while “PBDEs” (abbreviation of polybrominated biphenyl ethers), “PPCPs” (abbreviation of pharmaceuticals and personal care products) and “triclosan” just became hotspots in the last five years. New hotspots in the last five years partially indicated the trends in the sewage sludge research field, containing pop treatment methods (“drying”, “dewaterability”, “mesophilic” and “thermophilic”), research approaches (“pressurized liquid extraction”, “microwave” and “ultrasound”) and new energy resource (“Bio-oil” and “methane”).

3.4.2 Words in title analysis

Author keywords analysis may reveal the research hotspots, but some articles published on journals like *Environmental Science & Technology* do not have author keywords. Of 7233 articles analyzed in our research, only 5165 (71%) had author keywords. Meanwhile, The title of an article always contains the most important information the author wants to pass to the readers^{25,26,31}; therefore, analysis of words in title were used to evaluate research emphases as supplementary. When analyzing the words in titles, preconditioning was conducted firstly the same as analyzing the author keywords, then commonly appearing prepositions and conjunctions such as “of”, “in”, “and”, “for”, “on”, “from”, “to”, and “by”, articles including “the”, “a” and “an”, and common meaningless words such as “using” and “study” were discarded. Common expressions were linked together as one word, for instance, “sewage sludge” were changed to “sewage-sludge” and “heavy metal” turned to “heavy-metal”.

Of all the 9192 words used by different authors, “soil” (1834, 25%), “effect” (682, 9.4%), “sludge” (626, 8.7%), “compost” (612, 8.5%), and “organic” (589, 8.1%) were the most popular words, followed by “waste”, “heavy-metal”, “application”, “plant”, “treatment”, “municipal”, “anaerobic”, “wastewater”, “amended” and “production”, except for “sewage-sludge” and “biosolid”.

Figure 4 shows the pop title words co-occurrence network, which was different from the pop author keywords

Fig. 4. The pop title words co-occurrence network a) in 1991 – 2012; b) in 2008 – 2012. The weight of linked words is larger than 50 in 4a and 30 in 4b respectively. The size of node's symbol depended on the degree, and the size of the line denoted their weight. The top 20 title words in total during 1991 to 2012 are yellow in 4a, and the new words only appear in 4b are red.

Research trends in the sewage sludge field were separated into two categories – disposal and treatment methods, and contaminants. Referring to the disposal and treatment methods used in the sewage sludge research (Fig. 5a), “compost” had a distinctly higher incidence, which was mentioned in 1373 articles. Other disposal and treatment methods attracted significantly increasing attentions since 2000, especially “anaerobic digestion” with an increase from 13 articles in 2000 to 89 articles in 2012 and “pyrolysis” from only 1 article in 2000 and 31 articles in 2012. Referring to contaminants in sewage sludge (Fig. 5b), heavy metals including “Zn”, “Cu”, “Pb”, “Cd” and “Ni” were highlighted among contaminants, sharing similar growth trends. Organic matters owned less attention than heavy metals in sewage sludge research field. “PAHs” had received lots of attentions during 2002 to 2010 period. “PPCPs” and “PBDEs” became hotspots in 2005 and 2002 respectively, leading the trends of organic matter research in the sewage sludge field. In addition, “Pathogens” have attracted researchers' attentions since 2000.

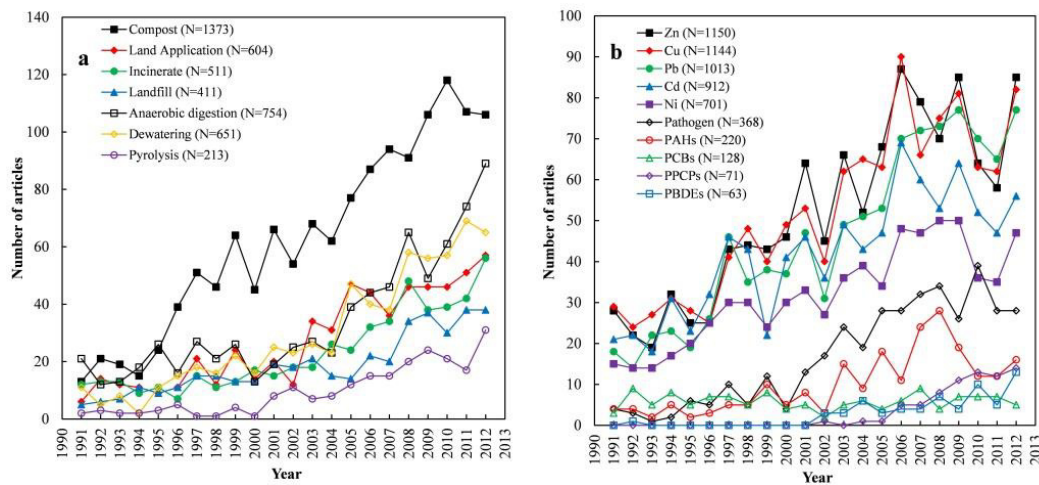


Fig. 5. Research trends of a) disposal and treatment methods: compost, land application, incinerate, landfill, anaerobic digestion, dewatering, pyrolysis; b) contaminants in sewage sludge: Zn, Cu, Pb, Cd, Ni, pathogen, PAHs, PCBs, PPCPs, PBDEs.

4 Conclusions

In this bibliometric study on sewage sludge, 8969 publications obtained from SCI-expanded database from 1991 to 2012 were analyzed to provide an overview of the publication performances and research emphases in the sewage sludge research field. An exponential model was established to indicate the stable publication trend with a high coefficient of determination of 0.977. The most productive journal was *Bioresour. Technology*. Five types of social networks were generated to visualize the publication performances and the research emphases including countries/territories, institute and author collaboration networks, author keywords and title words co-occurrence networks. USA ranked the first with respect to all indicators including total, single country, internationally collaborative, first author, corresponding author articles and degree. Author keywords co-occurrence network, title words co-occurrence network and hotspots analyses together indicated that “compost”, “anaerobic digestion” and “dewatering” were the most popular disposal and treatment methods. “Heavy metals” including “Zn”, “Cu”, “Pb”, “Cd” and “Ni” were the contaminants with the greatest concern. “Organic matters” such as “PPCPs” and “PBDEs” attracted comprehensive attention in recent years. “Soil” owned the most intimate relationship with sewage sludge due to its frequent appearance in titles and abstracts as an important approach for sewage sludge disposal.

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