RESEARCH ARTICLE

Global trends and future prospects of e-waste research: a bibliometric analysis

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Abstract

Electronic waste (e-waste) has been widely studied by scholars all over the world, but the research topics and development trends in this field are still unclear. This study aimed to explore the status quo, hot topics, and future prospects in the field of e-waste. Data of publications were downloaded from the Web of Science Core Collection. We used CiteSpace V, Histcite, and VOSviewer to analyze literature information. A total of 2800 papers in e-waste research were identified, and the number of publications increased rapidly after 2004. Six thousand five hundred seventy-three authors participated in the e-waste research, but 70.01% of the authors published only 1 article. The most productive country in this field was China (1146 publications), and the most productive institution was the Chinese Academy of Sciences (370 publications). The *Waste Management* (225 publications) was the most productive journal, and *Environment Science & Technology* (9704 co-citations) was the most co-cited journal. The main hot topics in e-waste field were management and recycling of e-waste in developing countries, health risk assessment after exposure to organic pollutants, degradation and recovery of waste metal materials, and impact of heavy metals on children's health. The frontier topic was degradation.

Keywords Bibliometric analysis · E-waste · Research trend · Web of Science · VOSviewer · CiteSpace

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Introduction

Electronic waste (e-waste), also known as waste electrical and electronic equipment, is defined as a waste from damaged or unwanted electrical or electronic devices (Grant et al. 2013; Man et al. 2013), including televisions, monitors, batteries, circuit boards, plastic casings, activated glass, lead capacitors, computers, audio and stereo equipments, video cameras, mobile phones, wireless devices, chips, motherboards, cathode ray tubes, and other peripheral items (Frazzoli et al. 2010; Grant et al. 2013). With the development of the electronic industry and the growing demand for information and tele-communications technologies, a large amount of e-waste is constantly being produced around the world (Duan et al. 2009; Frazzoli et al. 2010; Wang et al. 2013). Currently, e-waste is one of the fastest growing solid waste streams in the world, especially in China (Singh et al. 2016; Zeng et al. 2016). In 2014, the total amount of e-waste in the world was 41.8 Mt, which will increase to 50 Mt in 2018 (Lee et al. 2018). Consequently, large amounts of e-waste have brought global problems, causing environmental and food chain pollutions and shortage of ore, and posing a huge risk to human health (Frazzoli et al. 2010; Song and Li 2015).

Environmental pollutants can inhibit the activity of microbial enzymes, destroy the ability of microbial metabolism, weaken the resistance of microbial communities in the soil to subsequent disturbances, and reduce the diversity of microbial communities (Johnston and Leff 2015; Petric et al. 2011; Sullivan et al. 2013). In humans, the accumulation of metals and metalloids can cause physical damage: copper can cause liver damage; lead can interfere with behavior and learning ability; and cadmium can increase the risk of lung cancer and kidney damage (Chan and Wong 2013; Ramesh Babu et al. 2007; Song and Li 2015).

In recent years, researchers in different countries around the world have conducted many systematic reviews on the environmental and human impacts of different types of e-waste (Grant et al. 2013; Poole and Basu 2017), the recycling of e-waste (Ackah 2017), and the effects of harmful substances produced during the recycling process (Awasthi et al. 2018; Song and Li 2014). In addition, some studies have analyzed the global trends in food waste and solid waste by using bibliometric analysis (Chen et al. 2015; Yang et al. 2013; Zhang et al. 2018). However, there was no research to analyze the current status and future trends of e-waste research. Bibliometric analysis is defined as a tool for the statistical and quantitative analysis of research publications that can quantify the literature growth of specific subjects and the impact of individual research results, and is a good choice for assessing trends in research activities (Chen et al. 2015; Dalpe 2002; Liang et al. 2017; Ye et al. 2018). Furthermore, the bibliometric analysis focuses on the metrological characteristics of research literature in a given field (Ellegaard and Wallin 2015) and can assess the patterns of countries, institutions, journals, authors, and keywords related to a particular type of publication (Chen et al. 2016; Leefmann et al. 2016). This helps scholars seize the developmental characteristics of the field and guide their future work (Miao et al. 2018).

The present study aimed to (1) analyze the distribution of year, authors, countries, institutions, and journals on e-waste research; (2) identify the cooperation of countries and institutions; (3) and explore the existing hot topics and future prospects.

Methods

Data source and search strategy

Scientific output data was extracted from the Science Citation Index-Expanded (SCI-E) of the Web of Science Core Collection (WoSCC) on November 16, 2018. Data retrieval strategy is as follows: TS = ("electrical waste" OR "electrical wastes" OR "electronic waste" OR "electronic wastes" OR "e-waste" OR "waste electrical" OR "wastes electrical" OR "waste electronic" OR "wastes electronic" OR "electronic

rubbish" OR "electronic garbage" OR "electrical rubbish" OR "electrical garbage" OR "waste electrical and electronic equipment"). All searches were performed within the same day, to avoid the bias caused by the daily database updates. There were no restrictions on language, document type, data category, and publication year.

Statistical analysis

Publication characteristics, including document type, language, year, authors, co-cited authors, countries, institutes, journal sources, co-cited journals, keywords, and co-cited references, were analyzed by Histcite (version 2012.3.17) and VOSviewer (version 1.6.9) softwares. Co-cited authors mean that the authors are cited together, and co-cited references are references that have been co-cited in a set of publications. Microsoft Excel 2016 was used to analyze the publication trends. The polynomial model (trinomial model) was applied to forecast the growth of publications in the following year (Miao et al. 2018). VOSviewer software was used to analyze the relationships among the top productive countries, research institutions, and frequently used keywords (Zhang et al. 2018). In the current study, we reclassified articles from England, Northern Ireland, Scotland, and Wales to the UK and articles from Hong Kong, Macau, and Taiwan to China. We also performed cluster analysis and generated social network maps for countries, institutions, and keywords. Network maps consist of nodes and links. Different nodes in a map represent elements such as country, institution, and keywords. The size of the nodes reflects the number of publications or frequency, the larger the node, the greater the number of publications or frequency (Liang et al. 2018). The links between nodes represent relationships of collaboration, co-occurrence, or co-citations (Chen 2006; Xie 2015). The color of nodes and lines represents different clusters or years (Liang et al. 2017). CiteSpace V was used to identify co-occurrence keywords and co-cited references, capture keywords, and references with strong citation bursts. In the current study, the data was derived from the 50 most highly cited papers in a 1-year slice (Chen 2004).

The parameters of VOSviewer were as follows: counting method (fractional counting) and ignore documents with a large number of authors (maximum number of authors per document is 25).

Results

Document types and language of publication

Two thousand eight hundred publications were identified in SCI-E, which were divided into 10 document types. Full-length research articles were the main document type,

accounting for 83.54% of the included studies. The remaining publications were reviews (226, 8.07%), proceedings (88, 3.14%), editorial material (62, 2.21%), news item (33, 1.18%), meeting abstract (29, 1.04%), letter (13, 0.46%), book chapters (5, 0.18%), correction (4, 0.14%), and retraction (1, 0.04%). Of the 2800 included studies, 2749 (98.18%) were published in English, followed by German (10, 0.36%), Polish (10, 0.36%), Spanish (8, 0.29%), Portuguese (7, 0.25%), Chinese (6, 0.21%), French (4, 0.14%), Japanese (2, 0.07%), Croatian (1, 0.04%), and Czech (1, 0.04%).

Annual publications and growth forecast

The first study on e-waste was published in 1981 (Fig. 1), and before 2003, the number of publications per year was less than 8. After 2004, the number of researches increased rapidly, with the fastest growth rate from 2012 to 2013, and broke through 100 (3.57%) articles in 2009, 250 (8.93%) articles in 2013, and 428 (15.29%) articles in 2017. From 2009 to 2018, 2510 e-waste researches were published, accounting for 89.64% of all the included studies.

The polynomial model described the relationship between the publication year and the number of publications (Fig. 1). A significant correlation between the number of researches and the year was found with a high coefficient of determination ($R^2 = 0.9897$).

Authors and co-cited authors

A total of 6573 authors participated in the e-waste researches. Table 1 presented the top 10 authors and co-cited authors. Mai BX ranked first, with 94 (3.36%) publications, followed by Li

Table 1 The top 10 authors and co-cited authors in e-waste research (n (%))

Rank	Author	N (%)	Co-cited author	Citations
1	Mai BX	94 (3.36)	Cui JR	452
2	Li JH	84 (3.00)	Leung AOW	404
3	Luo XJ	83 (2.96)	Widmer R	342
4	Huo X	64 (2.29)	Li JH	342
5	Xu XJ	58 (2.07)	Robinson BH	320
6	Chen SJ	56 (2.00)	Zeng XL	306
7	Xu ZM	46 (1.64)	Li J	290
8	Wong MH	44 (1.57)	Wong MH	287
9	Li J	40 (1.43)	Nnorom IC	278
10	Zhang G	39 (1.39)	Song QB	257

JH (84 publications, 3.00%), Luo XJ (83 publications, 2.96%), Huo X (64 publications, 2.29%), Xu XJ (58 publications, 2.07%), and Chen SJ (56 publications, 2.00%). The remaining 4 authors published publications between 39 and 46. The top 6 co-cited authors were Cui JR (452 co-citations), Leung AOW (404 co-citations), Widmer R (342 co-citations), Li JH (342 co-citations), Robinson BH (320 co-citations), and Zeng XL (306 co-citations); other authors were cited less than 300.

Countries and institutions

In general, 84 countries participated in the publication of e-waste research, and China published the most research, accounting for 40.93% of the included studies, followed by the USA (345 publications, 12.32%), India (190 publications,

Fig. 1 Publication years and growth forecast for e-waste research
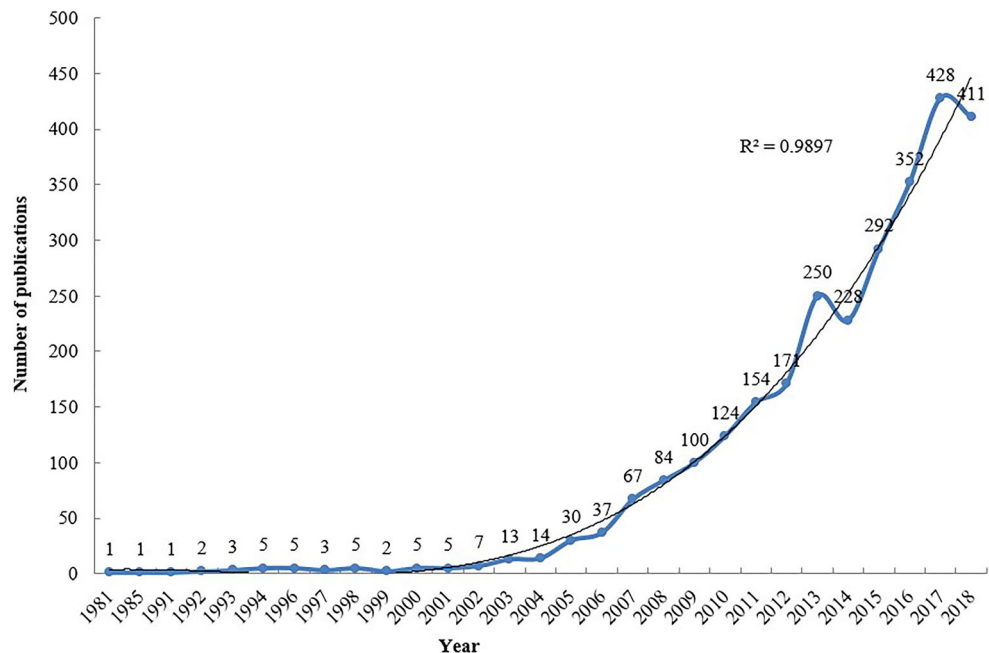
Table 2 The top 10 countries and institutions contributed to publications in e-waste research (*n* (%))

Rank	Country	N (%)	Institution	N (%)
1	China	1146 (40.93)	Chinese Academy of Sciences (China, Beijing)	370 (13.21)
2	USA	345 (12.32)	Tsinghua University (China, Beijing)	112 (4.00)
3	India	190 (6.79)	University of Chinese Academy of Sciences (China, Beijing)	78 (2.79)
4	UK	147 (5.25)	Shantou University (China, Guangdong)	73 (2.61)
5	Japan	135 (4.82)	Shanghai Jiao Tong University (China, Shanghai)	61 (2.18)
6	Australia	132 (4.71)	Hong Kong Baptist University (China, Hong Kong)	55 (1.96)
7	Germany	122 (4.36)	University of Jinan (China, Shandong)	46 (1.64)
8	Italy	91 (3.25)	Zhejiang University (China, Zhejiang)	45 (1.61)
9	Brazil	86 (3.07)	Sun Yat-sen University (China, Guangdong)	43 (1.54)
10	Netherlands	76 (2.71)	Ehime University (Japan, Ehime)	33 (1.18)

6.79%), the UK (147 publications, 5.25%), and Japan (135 publications, 4.82%) (Table 2). For the analysis of the social relations of countries with more than 4 articles, as can be seen from Fig. 2, 54 countries were clustered into eight categories, and the cooperation between countries was close.

Two thousand seventy-five institutions contributed to the publications of e-waste research. According to the list of top 10 institutions (Table 2), Chinese Academy of Sciences ranked first (370 publications, 13.21%), followed by Tsinghua University (112 publications, 4.00%), University of Chinese Academy of Sciences (78 publications, 2.79%), and Shantou University (73 publications, 2.61%). Figure 3 presented the collaborations of institutions with more than 12 articles; the main institutions were clustered into eight categories, but there was less cooperation between the groups.

Journals and co-cited journals

Two thousand eight hundred e-waste articles were published in 571 journals. Table 3 presented the top 10 journals and co-cited journals in e-waste research. *Waste Management* (225 publications, 8.04%) published the most papers, followed by *Journal of Cleaner Production* (148 publications, 5.29%), *Environment Science & Technology* (144 publications, 5.14%), and *Science*

of the Total Environment (121 publications, 4.32%). Of the top 10 journals, three were from the USA, the UK, and Netherlands, respectively, and one from Germany. The impact factors of the eight journals are higher than 4.000. *Environment Science & Technology* (9704 co-citations) was the most co-cited journal, followed by *Chemosphere* (5224 co-citations), and *Waste Management* (4950 co-citations). Of the top 10 co-cited journals, 50.00% were from the USA, 30.00% from the Netherlands, and 20.00% from the UK. Among them, the average impact factor (IF) is 5.758.

Figure 4 showed the dual-map overlay of journals. The left side represented the map of citing journals and the right side represented the map of the cited journals. The label represented the subject covered by the journal. Colored curves represent paths of references, originating from the citing map on the left and pointing to the cited map on the right (Chen et al. 2014a). There were five main citation paths shown on the map.

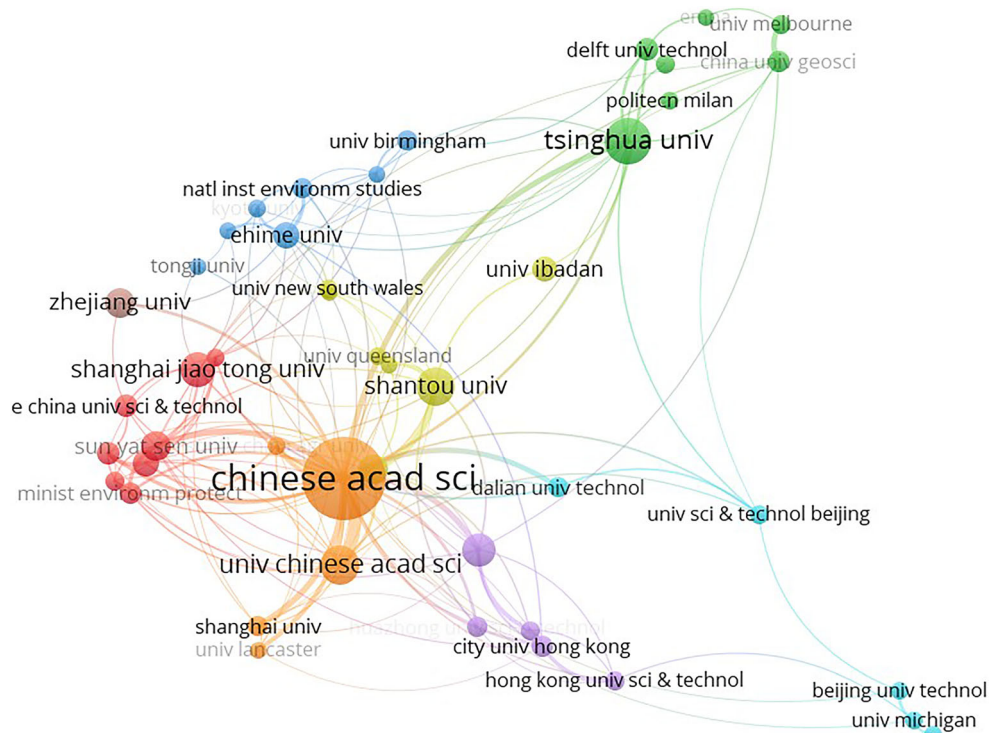## Co-occurrence keywords and burst keywords

A total of 9282 keywords appeared, but only 18 keywords with a frequency greater than 120. An analysis in terms of co-occurrence frequency (Table 4; Fig. 5a) revealed that the common keywords were electronic waste, polybrominated

Fig. 2 The network map of countries for e-waste research
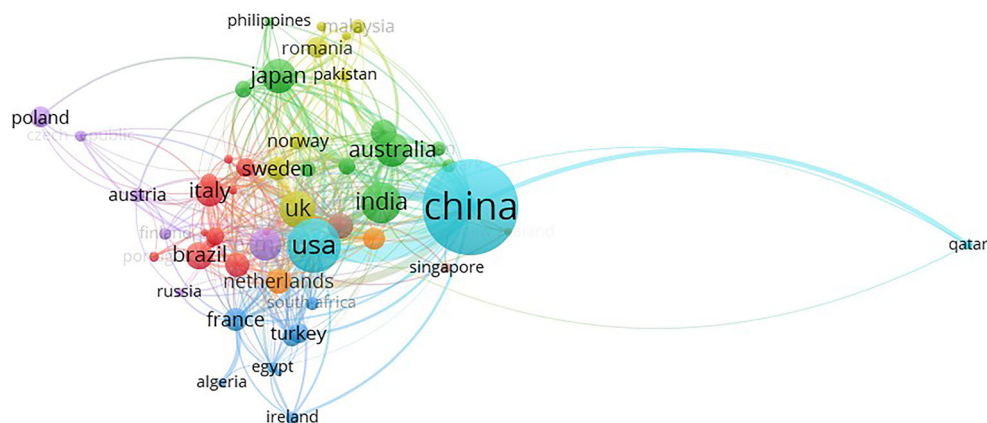
Fig. 3 The network map of institutions for e-waste research

diphenyl ethers, China, brominated flame retardants, management, recycling, recovery, printed-circuit boards, and heavy metals.

Clustering analysis was performed on co-occurrence keywords with a frequency greater than 35. Figure 5b showed that 96 keywords were clustered into four categories. Cluster 1 mainly focused on electronic waste, management, recycling, systems, and developing countries; cluster 2 mainly focused on polybrominated diphenyl ethers, brominated flame

retardants, dibenzo-P-dioxins, and human exposure; cluster 3 mainly focused on printed-circuit boards, copper, pyrosis, and recovery; and cluster 4 mainly focused on exposure, heavy metals, health, contamination, risk assessment, lead, and children.

Figure 6 presented the top 25 keywords with the strongest citation bursts. Among them, the first keyword with citation bursts appeared in 2005. Five keywords had citation bursts after 2008; they were "plastics" (2009–2013), "recycling site"

Table 3 The top 10 journals and co-cited journals in e-waste research (*n* (%))

| Rank	Journals	*N* (%)	Country	IF (2017)	Co-cited journals	Co-citation	Country	IF (2017)
1	Waste Management	225 (8.04)	USA	4.723	Environment Science & Technology	9704	USA	6.653
2	Journal of Cleaner Production	148 (5.29)	USA	5.651	Chemosphere	5224	UK	4.427
3	Environment Science & Technology	144 (5.14)	USA	6.653	Waste Management	4950	USA	4.723
4	Science of the Total Environment	121 (4.32)	Netherlands	4.610	Journal of Hazardous Materials	3765	Netherlands	6.434
5	Resources Conservation and Recycling	115 (4.11)	Netherlands	5.120	Science of the Total Environment	3295	Netherlands	4.610
6	Environmental Science and Pollution Research	112 (4.00)	Germany	2.800	Environmental Pollution	2851	UK	4.358
7	Chemosphere	101 (3.61)	UK	4.427	Environment International	2681	USA	7.297
8	Environmental Pollution	86 (3.07)	UK	4.358	Resources Conservation and Recycling	2390	Netherlands	5.120
9	Waste Management & Research	83 (2.96)	UK	1.631	Journal of Cleaner Production	2240	USA	5.651
10	Journal of Hazardous Materials	82 (2.93)	Netherlands	6.434	Environmental Health Perspectives	1724	USA	8.309
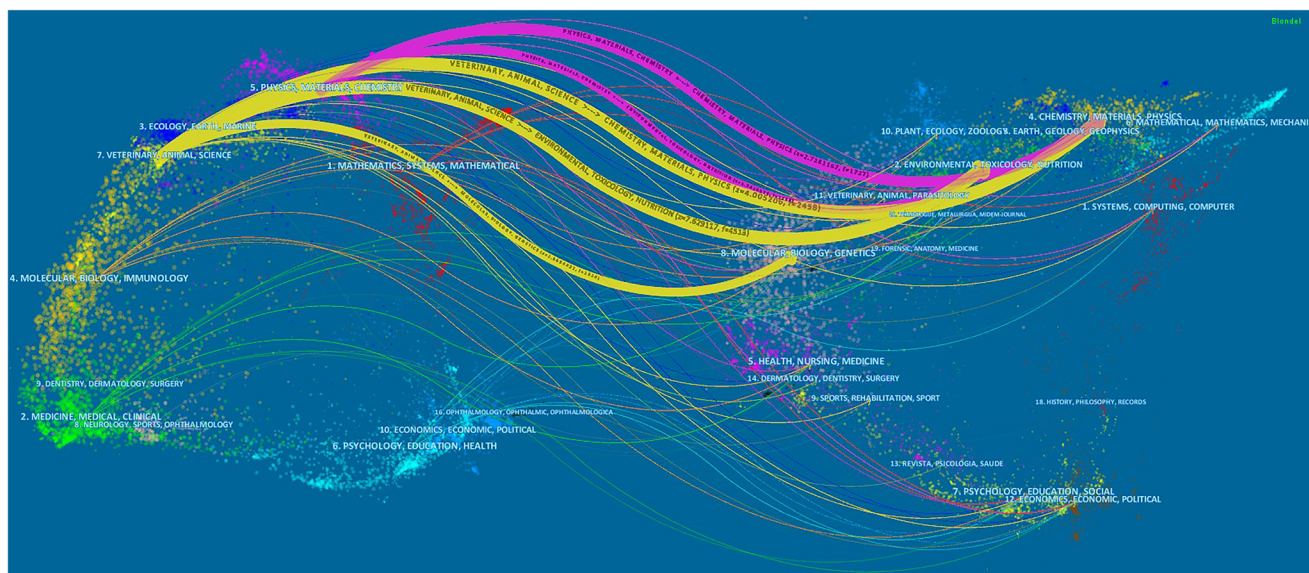
Fig. 4 The dual-map overlay of journals related to e-waste research

(2010–2015), "polychlorinated biphenyls" (2010–2013), "site" (2011–2014), and "degradation" (2014–2018).

Co-cited references and burst references

Table 5 revealed the top 10 co-cited references related to e-waste research. Two articles (Robinson 2009; Widmer et al. 2005) were co-cited more than 300 times, three articles (Cui and Zhang 2008; Leung et al. 2007; Wong et al. 2007) were co-cited between 200 and 270 times, and five articles (Cui and Forssberg 2003; Huo et al. 2007; Leung et al. 2006; Ongondo et al. 2011; Sepúlveda et al. 2010) were co-cited between 130 and 190 times.

Figure 7 presented the top 32 references with the strongest citation bursts. Among them, the first reference with citation bursts appeared in 2005; 59.38% of the articles appeared citation between 2007 and 2009, but after 2012, only two articles (Robinson 2009; Tsydenova and Bengtsson 2011) were detected with citation burst.

Discussion

The first e-waste research was published in 1981, but before 2003, there were only 45 articles related to e-waste in total, which indicates that e-waste research developed slowly during this period. After 2004, the number of researches increased rapidly, and in 2013, there was a peak in the amount of literature. This phenomenon may be due to an international working group meeting on e-waste and children's health held at the World Health Organization (WHO) headquarters in Geneva in June 2013, which promoted the reduction of exposure to harmful elements in e-waste and improved people's awareness of e-waste as a major environmental health threat (Heacock et al. 2016a). 89.64% of the researches were published between 2009 and 2018. With the increasing awareness of environmental protection, more and more countries and scholars have carried out e-waste research, which has led to a lot of e-waste research in recent years. A significant positive correlation was found between the number of studies and the

Table 4 The top 20 keywords in terms of frequency in e-waste research (n (%))

| Rank	Keyword	N (%)	Rank	Keyword	N (%)
1	Electronic waste	1455 (4.80)	11	South China	205 (0.68)
2	Polybrominated diphenyl ethers	532 (1.75)	12	Metals	205 (1.02)
3	China	422 (1.39)	13	Dibenzo-P-dioxins	160 (0.53)
4	Brominated flame retardants	310 (1.02)	14	Exposure	158 (0.52)
5	Recovery	310 (1.02)	15	Waste	144 (0.47)
6	Printed-circuit boards	302 (1.00)	16	Copper	139 (0.46)
7	Heavy metals	292 (0.96)	17	Soils	128 (0.42)
8	Recycling	281 (0.93)	18	Systems	128 (1.02)
9	Management	224 (0.74)	19	Lead	115 (0.38)
10	Polychlorinated-biphenyls	213 (0.70)	20	Human exposure	112 (0.37)

Fig. 5 a The density map and **b** network map of keywords for e-waste research
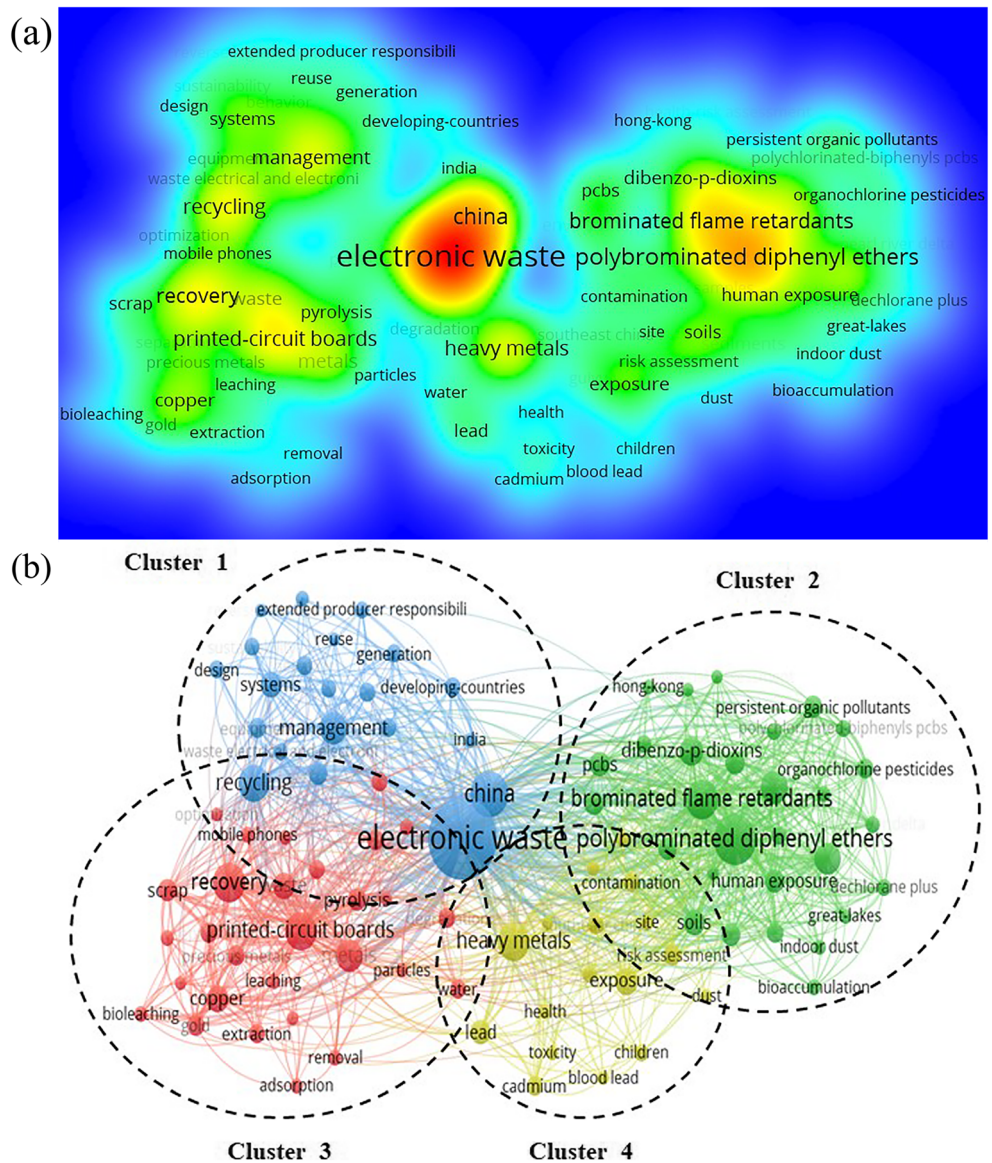
publication year; we can believe that research on e-waste will continue to grow in the coming years.

Six thousand five hundred seventy-three authors engaged in e-waste research between 1981 and 2018, while only 1.57% of the authors published more than 10 articles, and 70.01% of the authors published only 1 article, indicating that although many authors participated in the relevant research, there were, however, very few high-yield authors. The top 10 authors are all from China, indicating that Chinese scholars are active in this field and have many research results. However, among the top 5 co-cited authors, there were only two Chinese scholars. Although there were many high-yield scholars in China, there were not many co-cited authors. Therefore, Chinese scholars should strengthen cooperation with foreign scholars and innovate research methods to improve the quality of published papers.

Of the 2800 literatures, 40.93% were published by China. Among the top 10 countries, only 3 from the developing world show that e-waste research in developing countries is relatively backward except for China, so the developing countries should strengthen cooperation and exchanges with developed countries and learn advanced research methods and technologies to promote the development of e-waste research. What is more, funding for conducting meaning e-waste research should be made available to researchers in developing countries to increase the research output in the field of e-waste. Of the top 10 institutions, 9 were from China and 80.00% were Chinese universities. Currently, approximately 70% of the world's e-waste is processed in China (28 Mt/year) (Zhang et al. 2012). Crude e-waste recycling technology releases large amounts of persistent organic pollutants and heavy metals into the environment (Jiang et al. 2017; Luo
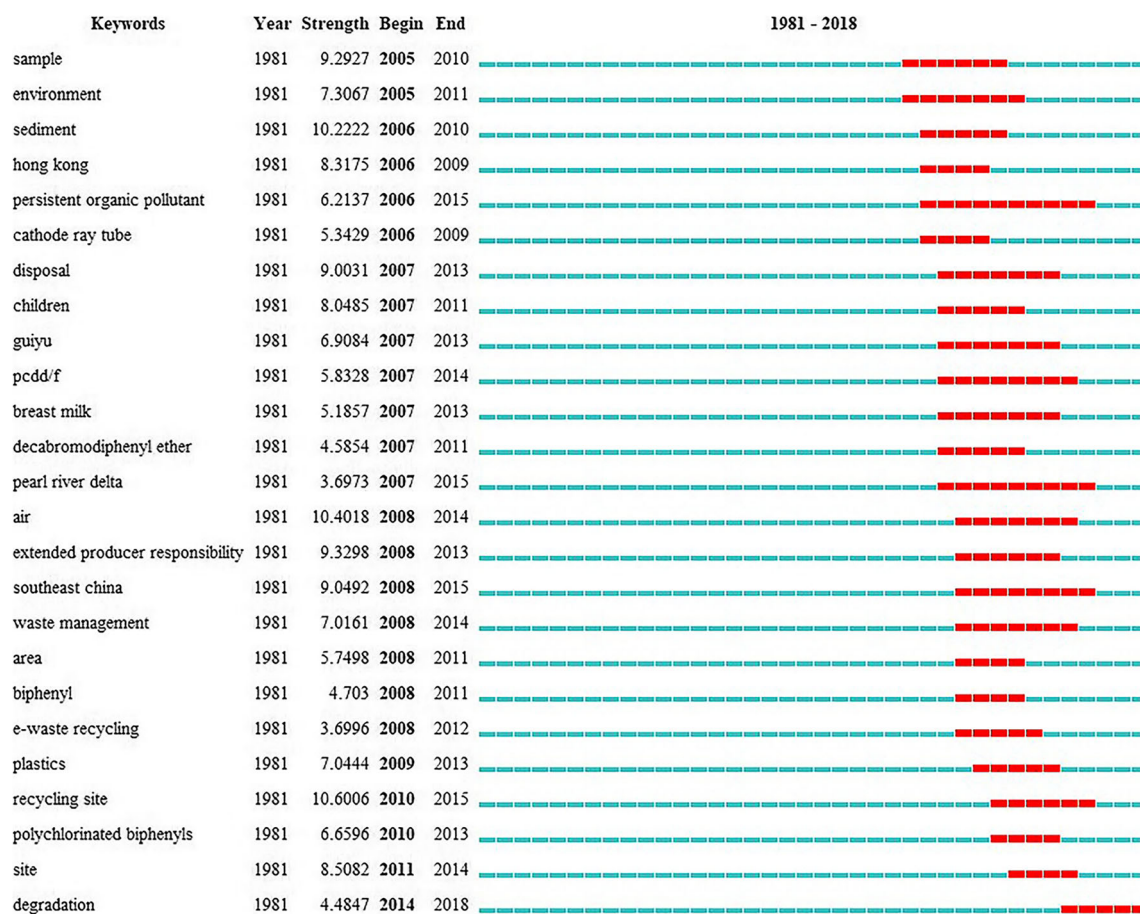
Fig. 6 Top 25 keywords with the strongest citation bursts. The red bars mean some keywords cited frequently; the green bars were keywords cited infrequently

et al. 2015; Wang et al. 2015), and incomplete combustion of e-waste leads to the release of polycyclic aromatic hydrocarbons (Lu et al. 2016; Wang et al. 2012; Yu et al. 2006), which pose a great threat to human health and ecosystems. Due to the fact that China processes a large percentage of e-waste, the environmental impacts seem to be significant to justify engagement in e-waste research by Chinese scholars.

The included e-waste studies were published in 571 journals, with an average of 4.90 papers published in each journal, but in fact, 73.20% of journals published one or two papers and only 6.30% of journals with more than 10 papers. It can be seen that there were imbalances in the journals that publish e-waste research, and there is a lack of journals that insist on publishing e-waste research. When two articles are cited simultaneously in one or more identical articles, the two articles have a co-citation relationship. Co-cited journals are those that are often cited together by other scholars. *Waste Management* was the journal with the largest number of e-waste researches, and its number of publications is 1.56 times that of *Environment Science & Technology*. However, *Environment Science & Technology* was the most co-cited journal, and its frequency of co-citation is 1.96 times that of *Waste Management*. The average impact factor of the top 10

co-cited journals was 5.758, the lowest impact factor was 4.427, and the impact factors of the 4 journals were greater than 6.000. This indicated that journals with a high impact factor were more often co-cited.

The examination of keywords in the current study indicates that 9282 were used from 1981 to 2018. There were 6574 keywords that appeared 1 time, and only 382 keywords with a frequency greater than 10, which indicates that the higher the frequency, the fewer the number of keywords, and the mainstream research on e-waste focused on a small area. Cluster analysis of keywords with a frequency greater than 35 indicates that there were four topics in e-waste research. Cluster 1 included 22 keywords, mainly related to the management and recycling of e-waste in developing countries. In many low- and middle-income countries, handling and disposal of discarded electronic equipment are often unregulated (Heacock et al. 2016b). Informal e-waste recycling is a source of much-needed income in many of these countries (Heacock et al. 2016a). However, its management in less-developed countries is often unsafe and leads to environmental pollution, which has a major impact on human health (Ackah 2017). In China, the phenomenon of recycling e-waste in unorganized sectors is still common, especially in Longtang, Guiyu, nearby Nanyang River and Beigang
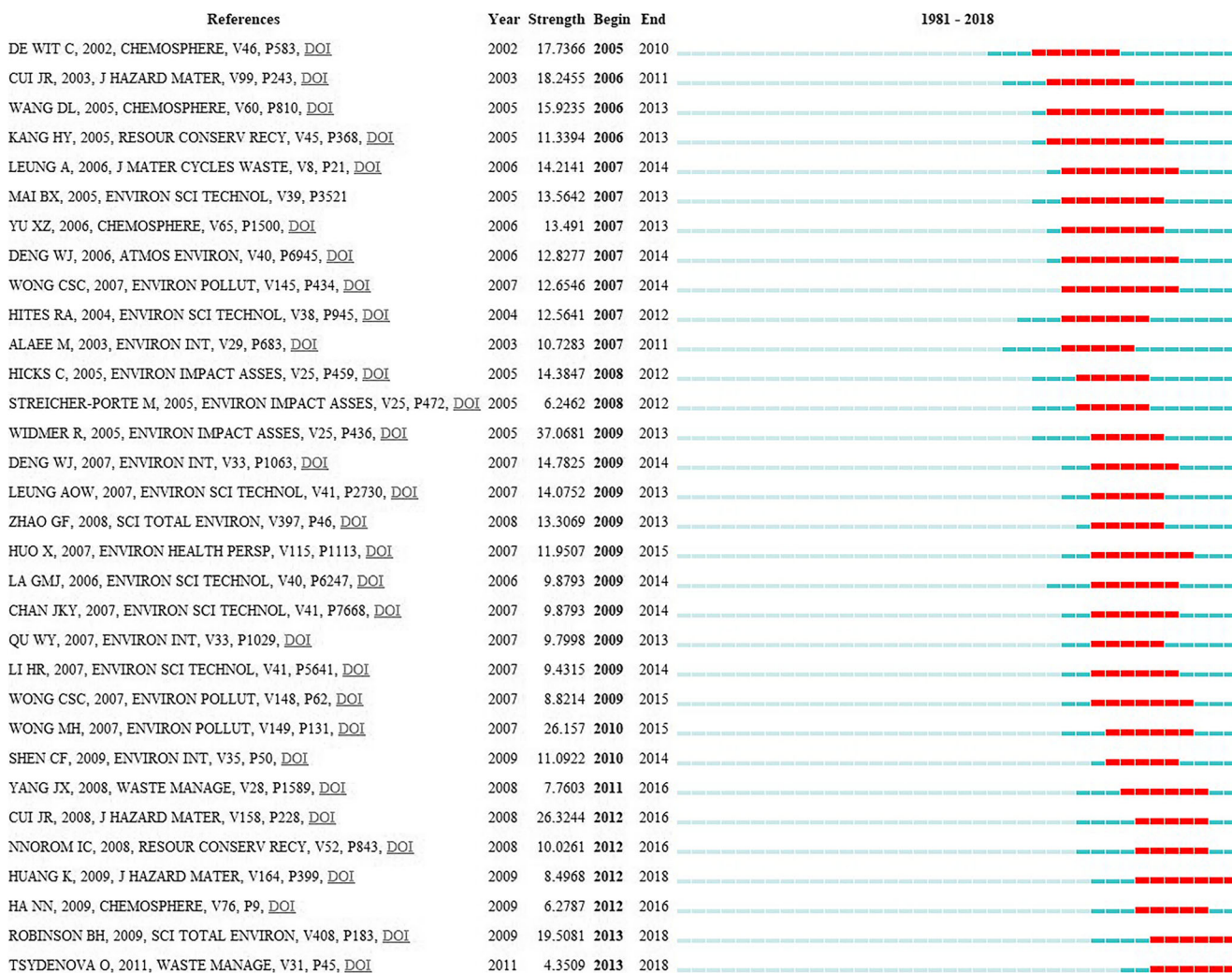
Table 5 Top 10 co-cited references related to e-waste research

Rank	Co-cited reference	Co-citation
1	Widmer R, 2005. Global perspectives on e-waste. Environmental Impact Assessment Review, V25, P436. (Widmer et al. 2005)	333
2	Robinson BH, 2009. E-waste: an assessment of global production and environmental impacts. Science of the Total Environment, V408, P183. (Robinson 2009)	315
3	Wong MH, 2007. Export of toxic chemicals - a review of the case of uncontrolled electronic-waste recycling. Environmental Pollution, V149, P131. (Wong et al. 2007)	270
4	Cui JR, 2008. Metallurgical recovery of metals from electronic waste: a review. Journal of Hazardous Materials, V158, P228. (Cui and Zhang 2008)	259
5	Leung AOW, 2007. Spatial distribution of polybrominated diphenyl ethers and polychlorinated dibenzo-P-dioxins and dibenzofurans in soil and combusted residue at Guiyu, an electronic waste recycling site in southeast China. Environment Science & Technology, V41, P2730. (Leung et al. 2007)	214
6	Cui JR, 2003. Mechanical recycling of waste electric and electronic equipment: a review. Journal of Hazardous Materials, V99, P243. (Cui and Forssberg 2003)	187
7	Ongondo FO, 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Management, V31, P714. (Ongondo et al. 2011)	180
8	Huo X, 2007. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environmental Health Perspectives, V115, P1113. (Huo et al. 2007)	154
9	Sepúlveda A, 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environmental Impact Assessment Review, V30, P28. (Sepúlveda et al. 2010)	133
10	Leung A, 2006. Environmental contamination from electronic waste recycling at Guiyu, southeast China. Journal of Material Cycles and Waste Management, V8, P21. (Leung et al. 2006)	132

River (Awasthi et al. 2018). In order to recover precious metals, strong acids are often used and discharged without proper treatment. Many harmful substances, including heavy metals and refractory organic substances, are released into the surrounding environment during the recycling process, causing great harm to local environment, ecosystems, and the health of residents (Li et al. 2018; Luo et al. 2017; Quan et al. 2014). Cluster 2 is the largest cluster, including 47 keywords, primarily related to the health risk assessment of humans after exposure to organic pollutants (e.g., polybrominated diphenyl ethers, brominated flame retardants, dibenzo-P-dioxins, and organochlorine pesticides). These organic pollutants are mainly released during the recovery process, usually from incineration and smelting (Frazzoli et al. 2010; Liu et al. 2008). They are usually lipophilic, persistent, bioaccumulative, long-lived, and therefore very resistant to damage (Grant et al. 2013; Mahmood et al. 2015). Previous studies have shown that organic pollutants are potentially harmful to ecosystems and human health, primarily affecting the nervous system and causing memory loss, and can also affect the human immune system (Jin et al. 2018; Xie et al. 2013). Cluster 3 included 28 keywords, focused on degradation and recovery of waste metal materials. With the rapid development of technology, more and more electronic products have been developed and applied in daily life. In particular, new applications such as hybrid or all-electric vehicles have led to a sharp increase in battery production (Lipman and Delucchi 2006). Therefore, it is important to improve the effectiveness and reduce the cost of the metal recycling process and to effectively control the amount of waste in the environment (Perez et al. 2016). Cluster 4 included 11 keywords,

mainly concerned about the impact of heavy metals on children's health. Children often face additional exposure risks due to additional exposure pathways such as breastfeeding and placental exposure, high-risk behaviors of hand-to-mouth activity, and high intake and low toxin elimination rates (Grant et al. 2013). Thus, the harm of heavy metals to children and how to reduce the exposure of children have received widespread attention.

In bibliometrics, a network graph of keyword co-occurrences can reflect hot topics, while burst keywords can represent frontier topics (Liang et al. 2017). The frontier topics represent the current state of development of a field (Chen 2006). We used CiteSpace V to capture the burst keywords; the first keyword with citation bursts appeared in 2005. Between 2009 and 2015, "plastics," "recycling site," "polychlorinated biphenyls," and "site" were the main frontier topics. However, after 2015, only one keyword with citation burst indicates that the scope of e-waste research is not broad enough and lacks emerging research topics. The dynamics of a field can be characterized in part by articles with citation bursts (Chen et al. 2014b). In e-waste research, the article with the strongest burst is associated with a study conducted by Widmer et al. (2005). This episode of burst started in 2009 and ended in 2013. This article is about the global perspectives of e-waste (Widmer et al. 2005). The most recent strongest burst started in 2013 is due to Robinson in 2009. This study assessed the global production of e-waste, the contaminants associated with e-waste, and the possible environmental impact of e-waste-associated contaminants (Robinson 2009). Among the top 32 burst references, 59.38% were first

References	Year	Strength	Begin	End	1981 - 2018
DE WIT C, 2002, CHEMOSPHERE, V46, P583, DOI	2002	17.7366	**2005**	2010	
CUI JR, 2003, J HAZARD MATER, V99, P243, DOI	2003	18.2455	**2006**	2011	
WANG DL, 2005, CHEMOSPHERE, V60, P810, DOI	2005	15.9235	**2006**	2013	
KANG HY, 2005, RESOUR CONSERV RECY, V45, P368, DOI	2005	11.3394	**2006**	2013	
LEUNG A, 2006, J MATER CYCLES WASTE, V8, P21, DOI	2006	14.2141	**2007**	2014	
MAI BX, 2005, ENVIRON SCI TECHNOL, V39, P3521	2005	13.5642	**2007**	2013	
YU XZ, 2006, CHEMOSPHERE, V65, P1500, DOI	2006	13.491	**2007**	2013	
DENG WJ, 2006, ATMOS ENVIRON, V40, P6945, DOI	2006	12.8277	**2007**	2014	
WONG CSC, 2007, ENVIRON POLLUT, V145, P434, DOI	2007	12.6546	**2007**	2014	
HITES RA, 2004, ENVIRON SCI TECHNOL, V38, P945, DOI	2004	12.5641	**2007**	2012	
ALAEE M, 2003, ENVIRON INT, V29, P683, DOI	2003	10.7283	**2007**	2011	
HICKS C, 2005, ENVIRON IMPACT ASSES, V25, P459, DOI	2005	14.3847	**2008**	2012	
STREICHER-PORTE M, 2005, ENVIRON IMPACT ASSES, V25, P472, DOI	2005	6.2462	**2008**	2012	
WIDMER R, 2005, ENVIRON IMPACT ASSES, V25, P436, DOI	2005	37.0681	**2009**	2013	
DENG WJ, 2007, ENVIRON INT, V33, P1063, DOI	2007	14.7825	**2009**	2014	
LEUNG AOW, 2007, ENVIRON SCI TECHNOL, V41, P2730, DOI	2007	14.0752	**2009**	2013	
ZHAO GF, 2008, SCI TOTAL ENVIRON, V397, P46, DOI	2008	13.3069	**2009**	2013	
HUO X, 2007, ENVIRON HEALTH PERSP, V115, P1113, DOI	2007	11.9507	**2009**	2015	
LA GMJ, 2006, ENVIRON SCI TECHNOL, V40, P6247, DOI	2006	9.8793	**2009**	2014	
CHAN JKY, 2007, ENVIRON SCI TECHNOL, V41, P7668, DOI	2007	9.8793	**2009**	2014	
QU WY, 2007, ENVIRON INT, V33, P1029, DOI	2007	9.7998	**2009**	2013	
LI HR, 2007, ENVIRON SCI TECHNOL, V41, P5641, DOI	2007	9.4315	**2009**	2014	
WONG CSC, 2007, ENVIRON POLLUT, V148, P62, DOI	2007	8.8214	**2009**	2015	
WONG MH, 2007, ENVIRON POLLUT, V149, P131, DOI	2007	26.157	**2010**	2015	
SHEN CF, 2009, ENVIRON INT, V35, P50, DOI	2009	11.0922	**2010**	2014	
YANG JX, 2008, WASTE MANAGE, V28, P1589, DOI	2008	7.7603	**2011**	2016	
CUI JR, 2008, J HAZARD MATER, V158, P228, DOI	2008	26.3244	**2012**	2016	
NNOROM IC, 2008, RESOUR CONSERV RECY, V52, P843, DOI	2008	10.0261	**2012**	2016	
HUANG K, 2009, J HAZARD MATER, V164, P399, DOI	2009	8.4968	**2012**	2018	
HA NN, 2009, CHEMOSPHERE, V76, P9, DOI	2009	6.2787	**2012**	2016	
ROBINSON BH, 2009, SCI TOTAL ENVIRON, V408, P183, DOI	2009	19.5081	**2013**	2018	
TSYDENOVA O, 2011, WASTE MANAGE, V31, P45, DOI	2011	4.3509	**2013**	2018	

Fig. 7 Top 32 references with the strongest citation bursts. The red bars mean some references cited frequently; the green bars were references cited infrequently

detected between 2007 and 2009, which suggests that this period may be the golden period for e-waste research. However, after 2012, only 2 references (Robinson 2009; Tsydenova and Bengtsson 2011) were discovered with citation bursts, probably because the existing topics have been thoroughly studied, but new research topics or new research methods have not been discovered.

Strengths and limitations

To the best of our knowledge, this paper is the first bibliometric analysis of e-waste research. We performed frequency analysis, cluster analysis, and hotspot analysis by using three kinds of visualization softwares, which clearly show the current status and future trends of e-waste research. But our research also has some limitations. Since WOS is considered to be the most important source of data for bibliometric analysis in science (Chen et al. 2015), we have only searched this database, and the included studies may not

be enough to represent all e-waste literature. Almost all of the included literature was published in English, which may lead to language bias. Since there are many authors and keywords in this study, although we have standardized and adjusted during the analysis, the omission may still exist.

Conclusions

The number of publications in e-waste research has been increasing over the years. Only a few were high-cited Chinese authors, although Chinese scholars are active in the e-waste field, and have published many articles. China, the USA, and India were the top three countries contributing to e-waste studies. Main countries were clustered into eight categories, and the cooperation between countries was close. Main institutions were also clustered into eight categories, but there was less cooperation between the groups. There are many journals that published e-waste research, but only a few were high-

yield journals. Management and recycling of e-waste in developing countries, health risk assessment after exposure to organic pollutants, degradation and recovery of waste metal materials, and impact of heavy metals on children's health are the main research topics in this field. In recent years, there have been fewer frontier topics, and relevant scholars should expand new research directions.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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