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PERSPECTIVES

Research performance and trends of fluorescent carbon nanoparticles: a science citation index expanded-based analysis

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Abstract A bibliometric approach to assess publication performances and trends in fluorescent carbon nanoparticle research using literatures in the Science Citation Index Expanded (SCI-EXPANDED) has been carried out. In order to ensure that these documents were related to fluorescent carbon nanoparticles, the filter, paper "front page" criteria were applied. Documents were analyzed, including document type and language of publication, publication trends, Web of Science categories and journals, publication of countries/regions and institutions, high impact and highly cited articles, and research hotspots and their trends. The total citations from Web of Science Core Collection since publication to the end of the most recent year and the total citations in the most recent year only were used to evaluate highly cited articles and high impact. Results found that the number of publications dramatically increased after 2011. Two Web of Science categories of multidisciplinary such as materials science and chemistry constituted the most of articles. *RSC Advances* was the most popular journal. Domination in publication is surprising from China and India. The top ten highly cited articles were the same as the top ten high-impact articles. Based on results of word analysis, word cluster was applied to hotspot and trend studies.

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Introduction

Graphite and active carbon are usually recognized as black solids without any luminescence. However, when carbon materials are cut into small sizes (mostly smaller than 10 nm) and properly functionalized, their optical properties are dramatically changed. Early in 2006, Prof. Ya-Ping Sun proposed the concept of carbon dots, fluorescent carbon nanoparticles with surface passivation (Sun et al. 2006). Carbon dots possess the competitive optical properties to semiconductor quantum dots such as CdSe, but are much more biocompatible and nontoxic. Therefore, carbon dots are regarded as hopeful new material platforms for bioimaging and other applications (Yang et al. 2009a, b; Luo et al. 2013). Biomedical applications of carbon dots in cell imaging (Cao et al. 2007), in vivo imaging (Yang et al. 2009a, b), and theranostics (Huang et al. 2012) are quickly established ever since that. Another category of intrinsic fluorescent carbon nanoparticles is graphene quantum dots, which emit luminescence from bandgap transitions of conjugated π-domains and the passivation of defects (Cao et al. 2013). The two intrinsic fluorescent carbon nanoparticles, carbon dots, and graphene quantum dots, have attracted tremendous interest and been applied in bioimaging, for example imaging (Peng et al. 2017), drug delivery (Chaudhary et al. 2017), analysis (Wang, et al. 2017), sensors (Atabaev 2018), energy conversion

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(Essner and Baker 2017), and catalysis (Hutton et al. 2017). Due to the rapid development of fluorescent carbon nanoparticles, many review papers are published to summarize the research progresses and indicate the future directions (LeCroy et al. 2016; Luo et al. 2014). Despite the common reviews, bibliometric methods provide in-depth analysis of the literature output and research trends.

Kostoff's group presented a series of bibliometric studies in material field by Science Citation Index Expanded (SCI-EXPANDED) (Kostoff et al. 2002,2006,2007a,2007b). Highly cited articles in materials science were also reported (Ho 2014). Bibliometric studies of publications related to nanoparticles have been presented including the review of nanoparticle drug delivery technologies (Lee et al. 2016), the development trends and research fronts of magnetic nanoparticles (Liu et al. 2016), the review of nanoparticles toxicity on algae (Tang et al. 2018), and bibliometric of the reproductive and developmental toxicity of nanoparticles (Wang et al. 2018).

In the present study, the fluorescent carbon nanoparticle publications were analyzed based on papers indexed in SCI-EXPANDED. Publication performance of countries and institutions as well as the publication hotspots and their trends were discussed.

Materials and methods

Data used in this study were retrieved from the Clarivate Analytics Web of Science, the online version of the Science Citation Index Expanded (SCI-EXPANDED) on 21 September 2018. The database was searched under the strategy:

> TOPIC: ("graphene nanodot" or "graphene nanodots" or "graphene dots" or "graphene dot" or "graphene quantum dot" or "graphene quantum dots" or "carbon dots" or "carbon dot" or "carbon quantum dot" or "carbon quantum dots" or "carbon nanodot" or "carbon nanodots" or "C nanodot" or "C nanodots") and ("fluorescent" or "fluorescence" or "photoluminescence" or "photoluminescent" or "luminescence" or "luminescent" or "phosphorescence" or "phosphorescent") and year published: 2006–2017

KeyWords Plus supplied additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI (now Clarivate Analytics) databaseand substantially augmented title-word and author-keyword indexing (Garfield 1990). The final filter was the "front page" (Fu et al. 2012) in which only the articles having the search keywords in their "first page" including article title abstract and author keywords were retained. The impact factor of a journal was based on the *Journal Citation Report* 2017 (IF_{2017}). The number of citations of an article from Web of Science Core Collection in a single year for example 2017 was referred to as the C_{2017} (Ho 2012) and the total number of citations since publication to the end of 2017 was referred to as the TC_{2017} (Wang et al. 2011; Chuang et al. 2011). The records were downloaded and reorganized using Microsoft Excel 2016 (Li and Ho 2008; Ho and Fu 2016). In the SCI-EXPANDED database, the corresponding author was designated as the "reprint author"; this study instead used the term "corresponding author" (Chiu and Ho 2007). In a single-author article where authorship was unspecified, the single author was both first author and corresponding author. Similarly, for a single institution article, the institution was classified as both the first author's institution and the corresponding author's institution (Lin and Ho 2015). Only the first corresponding author was considered in this study. The collaboration type was determined by the addresses of the authors.

Results and discussion

Document type and language of publication

A relationship between document types and their citations per publication in a research field was proposed (Hsieh et al. 2004). A total of 2933 fluorescent carbon nanoparticles related publications in SCI-EXPANDED was found within eight document types indexed in the Web of Science. The most used document type was the articles (95% of 2933 publications) followed distantly by reviews (3.5%) and meeting abstracts (1.1%) (Table 1). A total of 33 meeting abstracts were published in ten journals in which *Abstracts of Papers of the American Chemical Society* published the most meeting abstracts with 16 (48% of 33 meeting abstracts). Similarly, *TRAC-Trends in Analytical Chemistry* published the most reviews with seven (6.9% of 102 reviews). The document type of reviews had the highest CPP_{2017} of 71 which can be attributed to the reviews entitled

Table 1 Citations and authors according to document type

Document type	TP	%	APP	CPP_{2017}
Article	2775	95	6.0	27
Review	102	3.5	4.0	71
Meeting abstract	33	1.1	4.2	0.091
Correction	13	0.44	5.4	0.54
Proceedings paper	13	0.44	3.9	15
Editorial material	7	0.24	2.4	5.0
Letter	3	0.10	4.0	3.3
Retracted publication	2	0.068	4.5	3.0

TP number of articles, *AU* number of authors, *APP* number of authors per publication (*APP*), CPP_{2017} citations per paper (TC_{2017}/TP), TC_{2017} total citations from Web of Science Core Collection since publication to the end of 2017

"Luminescent carbon nanodots: Emergent nanolights" (Baker and Baker 2010) by Sheila N. Baker and Gary A. Baker from Oak Ridge National Laboratory in USA with the highest TC_{2017} of 1796 in fluorescent carbon nanoparticles related publications. The highest number of authors per publication (*APP*) was a document of articles with 6.0 and followed by corrections (5.4). Document of articles represented whole research ideas and results, therefore 2775 articles were analyzed in further study (Ho et al. 2010). Language of publication in a research field is one of the basic concerns in bibliometric studies as a big data analysis (Wang and Ho 2011). Ninety-nine percent of the articles were published in English with CPP_{2017} of 27 and *APP* of 6.0. Other two non-English languages were also used, such as Chinese (36 articles; CPP_{2017} = 2.4; *APP* = 4.8) and Portuguese (1 article; CPP_{2017} = 3.0; *APP* = 5.0). Such high percentage (99%) of English articles was also reported in wetland research (Zhang et al. 2010a) and ammonia oxidation (Zheng et al. 2017).

Trends in fluorescent carbon nanoparticle publications

A relationship between the percentage of cited papers and paper life has been reported (Chiu and Ho 2005). In order to understand publication and their citation trends, a relationship between citations per publication (CPP_{2017}) and article life was further proposed (Chuang et al. 2007). Generally, after publication year, CPP_{2017} of articles sharply increased to a peak and decreased after that (Chuang et al. 2007; Chuang and Ho 2014). However, Fig. 1 shows citations per publication for each year of article life up to the 11th year, which was the last year with only one article.

Ho proposed a relationship between total number of articles (*TP*) in a year and their citations per publication (CPP_{year} = TC_{year}/TP) by the decades (Ho 2012) and years (Ho 2013) to understand publication and their impact trends in a research field. It was applied as a unique indicator for research topics (Pouris and Ho 2016; Ho et al. 2016). The annual number of fluorescent carbon nanoparticle-related articles in SCI-EXPANDED and their CPP_{2017} were counted and is displayed in Fig. 2. In the period of 2006–2008, only one article was published in each year including articles by Sun et al. (2006), Cao et al. (2007), and Sun et al. (2008) with TC_{2017} of 1620, 1035, and 170, respectively. After 2010, a sharp increase was found from 30 in 2011 to 846 in 2017.

Web of science categories and journals

Distributions of Web of Science category and journal are a basic part of bibliometric study (Chiu and Ho 2005). The fluorescent carbon nanoparticle articles published in journals that were distributed in 65 Web of Science categories in SCI-EXPANDED. The top 11 productive Web of Science categories with more than 100 articles are shown in Table 2. Thirty-eight percent of all articles were published in leading two categories such as multidisciplinary materials science with 929 articles (33% of 2775 articles) and multidisciplinary chemistry with 878 (32%) articles. It should also be noticed that journals

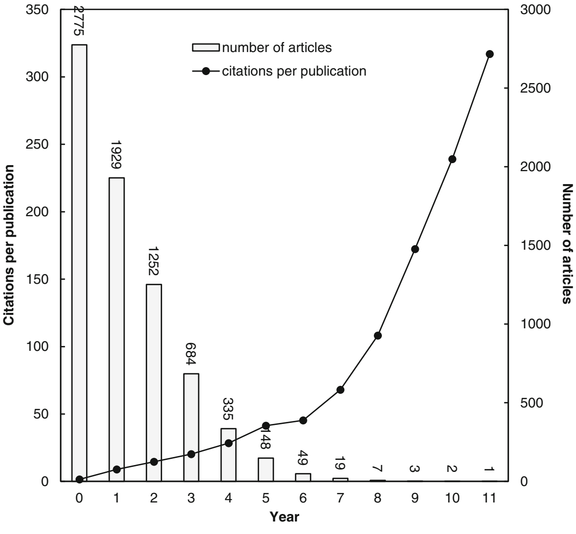

Fig. 1 Citations per publication by article age

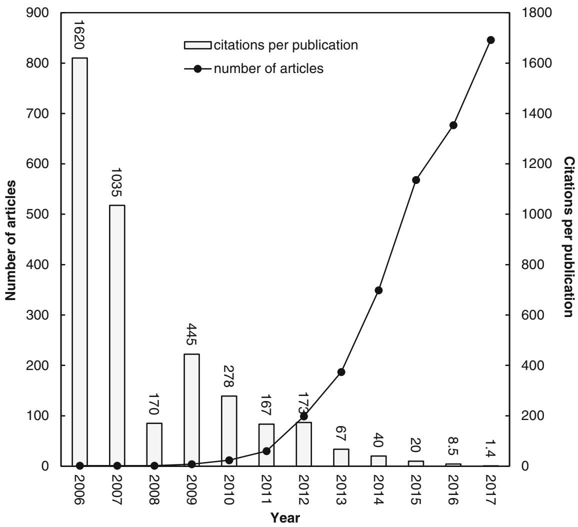

Fig. 2 Trends of fluorescent carbon nanoparticles articles in SCI-EXPANDED and citations per publication from 2006 to 2017

could be classified into two or more categories in Web of Science (Ho 2014), for example *Biosensors & Bioelectronics* was listed in categories of "biophysics," "biotechnology and applied microbiology," "analytical chemistry," "electrochemistry," and "nanoscience and nanotechnology" thus the sum of percentages was higher than 100%. The percentages of the top categories were high, which indicated the research focused on specific research areas including chemistry and materials science.

In total, 2775 fluorescent carbon nanoparticle articles were published in 319 journals in SCI-EXPANDED. The top ten most productive journals are listed in Table 3. Four of the top ten productive journals were in Web of Science category of multidisciplinary materials science and three in each of nanoscience and nanotechnology, analytical chemistry, and multidisciplinary chemistry respectively. *RSC Advances* (IF_{2017} = 2.936)

Table 2 Top 11 active Web of Science categories

Web of Science category	TP	%	No. J
Multidisciplinary materials science	929	33	285
Multidisciplinary chemistry	878	32	171
Nanoscience and nanotechnology	668	24	92
Analytical chemistry	605	22	80
Physical chemistry	512	18	146
Applied physics	458	17	146
Electrochemistry	245	8.8	28
Biomaterials materials science	162	5.8	33
Instruments and instrumentation	137	4.9	61
Condensed matter physics	126	4.5	67
Biophysics	109	3.9	72

TP number of total articles, *No. J* number of journals in a category

Table 3 The top ten productive journals on graphene nanodots research

Journal	*TP* (%)	IF_{2017}	Web of Science category
RSC Advances	288 (10)	2.936	Multidisciplinary chemistry
Nanoscale	136 (4.9)	7.233	Multidisciplinary chemistry Nanoscience and nanotechnology Multidisciplinary materials science Applied physics
Sensors and Actuators B-Chemical	132 (4.8)	5.667	Analytical chemistry Electrochemistry Instruments and instrumentation
ACS Applied Materials & Interfaces	112 (4.0)	8.097	Nanoscience and nanotechnology Multidisciplinary materials science
Biosensors & Bioelectronics	91 (3.3)	8.173	Biophysics Biotechnology and applied microbiology Analytical chemistry Electrochemistry Nanoscience and nanotechnology
Journal of Materials Chemistry B	91 (3.3)	4.776	Biomaterials materials science
Carbon	77 (2.8)	7.082	Physical chemistry Multidisciplinary materials science
Chemical Communications	67 (2.4)	6.290	Multidisciplinary chemistry
Journal of Materials Chemistry C	66 (2.4)	5.976	Multidisciplinary materials science Applied physics
Microchimica Acta	65 (2.3)	5.705	Analytical chemistry
RSC Advances	288 (10)	2.936	Multidisciplinary chemistry

TP number of total articles, IF_{2017} journal impact factor in 2017 in the category of multidisciplinary chemistry, published the most fluorescent carbon nanoparticles articles (288 articles; 10% of 2775 articles). As regards to journal impact factor, *Nature Nanotechnology* won the first place with the highest IF_{2017} of 37.49 with two articles, followed by *Energy & Environmental Science* (IF_{2017} = 30.067) with one article, *Materials Today* (IF_{2017} = 24.537) with three articles, and *Advanced Materials* (IF_{2017} = 21.95) with 20 articles.

Publication of countries/regions

The contributions provided by different countries were estimated by the affiliation of at least one author of fluorescent carbon nanoparticle articles. Of the 2773 articles with author affiliations in SCI-EXPANDED published by authors from 59 countries, 2355 articles (85% of 2773 articles) were country-independent publications from 36 countries, and 418 (15%) articles were internationally collaborative publications from 58 countries. Five bibliometric indicators such as the total (*TP*), independent (*IP*), collaborative (*CP*), first author (*FP*), and corresponding author (*RP*) were applied to examine the research performances for different countries (Han and Ho 2011). Table 4 shows the top ten productive countries including one American country, two European countries, six Asia countries, and Australia. Only two of the seven major industrialized countries of the world (G7) such as USA and Germany were ranked in the top ten but Japan (36 articles; ranked 11th), the UK (31 articles; ranked 12th), Italy (27 articles; ranked 13th), Canada (17 articles; ranked 19th), and France (11 articles; ranked 24th), were not at the top. China ranked top in six publication indicators with *TP* of 1866 articles (67% of 2773 articles), *IP* of 1610 articles (68% of 2355 independent articles), *CP* of 256 articles (61% of 418 collaborative articles), *FP* of 1811 articles (65% of 2773 first author articles), and *RP* of 1801 articles (65% of 2773 corresponding author articles).

Publication of institutions

The five publication indicators were used to compare institution publications (Han and Ho 2011). In total, 1261 (45% of 2773 articles) were single institution articles and 1512 (55%) articles were inter-institutional collaborations. The top ten institutions were ranked by the number of total articles in Table 5. Among these ten institutions, nine were in China and one in India. Chinese Academy of Sciences in China with 324 articles (12% of 2773 articles) including 282 inter-institutionally collaborative articles (19% of 1512 articles), 187 first author articles (6.7% of 2773 articles), and 201 corresponding author articles (7.2% of 2773 articles), ranked top while Jilin University in China with the most institutional independent articles with 58 (4.6% of 1261 articles). In addition, Indian Institutes of Technology in India with 56 articles (ranked fifth) was the only one non-Chinese institute in Table 5. A bias appeared because both the Chinese Academy of Sciences (Li et al. 2009) and the Indian Institute of Technology (Tanaka and Ho 2011) have branches in different cities.

Table 4 Top ten productive countries

Country	TP	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)
China	1866	1 (67)	1 (68)	1 (61)	1 (65)	1 (65)
India	271	2 (9.8)	2 (10)	6 (6.9)	2 (9.3)	2 (9.3)
USA	240	3 (8.7)	4 (3.3)	2 (39)	4 (3.7)	4 (3.9)
South Korea	124	4 (4.5)	3 (3.9)	4 (7.7)	3 (4.0)	3 (4.1)
Iran	81	5 (2.9)	5 (2.9)	16 (2.9)	5 (2.9)	5 (2.9)
Taiwan	80	6 (2.9)	6 (2.5)	11 (4.8)	6 (2.6)	6 (2.5)
Australia	56	7 (2.0)	14 (0.42)	3 (11)	9 (0.87)	9 (0.94)
Spain	55	8 (2.0)	7 (1.1)	7 (6.7)	7 (1.5)	7 (1.7)
Singapore	41	9 (1.5)	8 (0.72)	8 (5.7)	8 (1.0)	8 (1.0)
Germany	38	10 (1.4)	16 (0.34)	5 (7.2)	10 (0.72)	11 (0.69)

TP total number of articles, *TPR* (%), *IPR* (%), *CPR* (%), *FPR* (%), *RPR* (%), and *RPR* (%): the rank and percentage of total articles, country independent articles, internationally collaborative articles, first author articles, corresponding author articles, and single author articles among their total articles, respectively

Table 5 Top ten productive institutions

Institute	TP	*TPR* (%)	*IPR* (%)	*CPR* (%)	*FPR* (%)	*RPR* (%)
Chinese Academy of Sciences, China	324	1 (12)	3 (3.3)	1 (19)	1 (6.7)	1 (7.2)
Jilin University, China	112	2 (4.0)	1 (4.6)	3 (3.6)	2 (3.2)	2 (3.2)
University of Chinese Academy of Sciences, China	97	3 (3.5)	69 (0.32)	2 (6.2)	89 (0.25)	86 (0.25)
Southwest University, China	73	4 (2.6)	2 (3.8)	11 (1.7)	3 (2.6)	3 (2.6)
Indian Institutes of Technology, India	56	5 (2.0)	4 (2.6)	15 (1.5)	5 (1.6)	5 (1.5)
Lanzhou University, China	54	6 (1.9)	7 (1.5)	5 (2.3)	4 (1.8)	4 (1.8)
Nanjing University, China	53	7 (1.9)	10 (1.3)	4 (2.4)	6 (1.4)	6 (1.4)
Soochow University, China	46	8 (1.7)	7 (1.5)	8 (1.8)	7 (1.3)	7 (1.3)
Shanghai Jiao Tong University, China	39	9 (1.4)	17 (1.0)	8 (1.8)	10 (0.90)	10 (0.90)
Shanghai University, China	38	10 (1.4)	25 (0.79)	7 (1.9)	14 (0.83)	25 (0.65)

TP: total number of articles; *TPR* (%), *IPR* (%), *CPR* (%), *FPR* (%), *RPR* (%): the rank and percentage of total articles, single-institution articles, inter-institutionally collaborative articles, first-author articles, and corresponding-author articles among their total articles, respectively; N/A: not available

At present, the publications of these two institutes were pooled as one heading, and publications divided into branches would result in different rankings (Li et al. 2009). Except for the Chinese Academy of Sciences and the Indian Institute of Technology, Jilin University in China ranked the top in *TP*, *IP*, *FP*, and *RP*. University of Chinese Academy of Sciences in China published the most inter-institutionally collaborative articles. Low percentage of independent articles with *IP* of four articles (ranked 69th, 0.32% of 1261); first author articles with *FP* of seven articles (ranked 89th, 0.25% of 2773); and corresponding author articles with *RP* of seven articles (ranked 86th, 0.25% of 2773) shows that University of Chinese Academy of Sciences had low research capacity in fluorescent carbon nanoparticle research. Figure 3 shows the publication trends of the top seven institutes. Jilin University, Southwest University, and Indian Institute of Technology had similar increasing trends. Chinese Academy of Sciences and University of Chinese Academy of Sciences also had a similar development trend, especially a decreasing trend was found in the recent year.

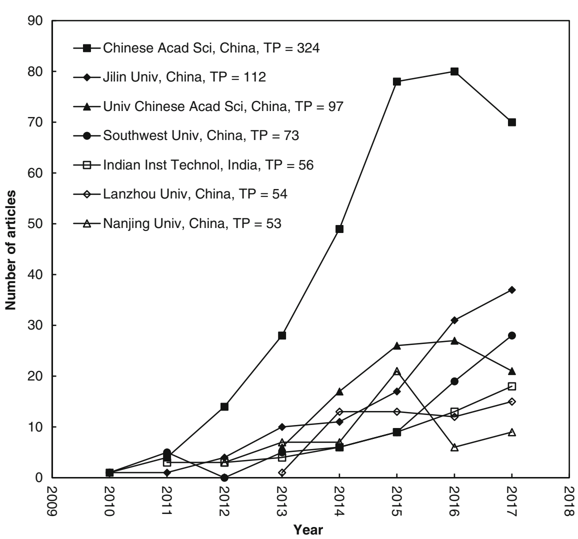

Fig. 3 Publication trends of the top seven institutes (*TP* > 50)

High impact and highly cited articles

It was recommended that researchers pay more attention to the highly cited articles with C_{year} but not to those with TC_{year}, because some highly cited articles with TC_{year} have not had a high impact in recent years (Ho and Hartley 2016). However, the top ten highly cited articles in fluorescent carbon nanoparticles still have a high impact in the most recent year with $C_{2017} \geq 169$ (ranked top ten) including articles as follows (Fig. 4):

1. Quantum-sized carbon dots for bright and colorful photoluminescence (Sun et al. 2006)

This most impact article in 2017 was published by Sun and other 15 authors from Clemson University in the USA with C_{2017} of 317 (ranked first) and TC_{2017} of 1620 (ranked first). In this communication, Prof. Ya-Ping Sun and co-workers proposed for the first time the concept of carbon dots and demonstrated the

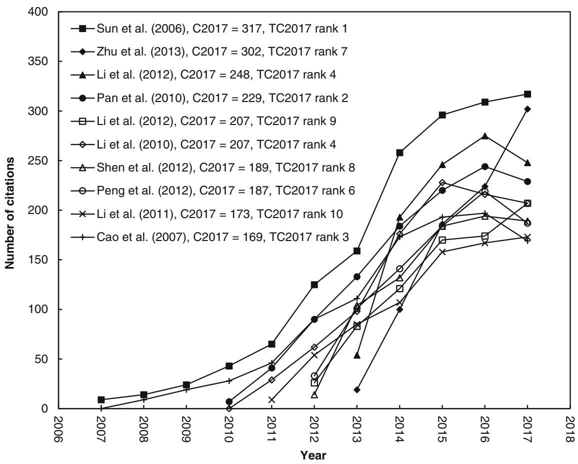

Fig. 4 The citation histories of the articles ranked top ten in both C_{2017} and TC_{2017}

photoluminescence of carbon dots. Acid-treated carbon particles from laser ablation were functionalized with diamine-terminated oligomeric poly-(ethylene glycol). The polymer passivated the defects on carbon nanoparticles to produce emissive energy traps on the surface of carbon dots. Carbon dots emitted fluorescence with quantum yields of 4%–10% and the emission wavelengths shifted along with the change of excitation wavelengths. The luminescence of carbon dots was stable against photo-irradiation. The bioimaging applications of carbon dots were confirmed by the colorful bacteria and mammalian cells upon the incubation with carbon dots.

2. Highly photoluminescent carbon dots for multicolor patterning, sensors, and bioimaging (Zhu et al. 2013)

The article was published by Zhu and other nine authors from Jilin University in China with C_{2017} of 302 (ranked second) and TC_{2017} of 831 (ranked seventh). In this communication, Zhu and co-workers reported a facile and high output strategy for the industrial-scale production of carbon dots, and developed several new applications of carbon dots. Citric acid and ethylenediamine were hydrothermally reacted to produce carbon dots with a high quantum yield of 80%. Interestingly, carbon dots were applied in multicolor patterning as printing inks at microscale. Carbon dots could also be fabricated into polymers for anti-counterfeit purposes. The fluorescence of carbon dots could be selectively quenched by Fe^{3+}, so carbon dots were used for intracellular Fe^{3+} detection. In all aforementioned applications, carbon dots were excited by UV blue and green light to emit blue, green, and red fluorescence.

3. Carbon nanodots: synthesis, properties, and applications (Li et al. 2012a)

The article was published by Li and other three authors from Soochow University in China with C_{2017} of 248 (ranked third) and TC_{2017} of 1016 (ranked fourth). This is a feature article, in which Li et al. reviewed the synthesis, properties, and applications of carbon dots. It is mistakenly categorized as an article in SCI-EXPANDED database. The chemical and physical synthesis methods of carbon dots were summarized. The optical properties of carbon dots, including absorbance, photoluminescence, electrochemical luminescence, photo-induced electron transfer property, and upconversion photoluminescence were introduced. The applications of carbon dots in photocatalysis, optoelectronics, energy and charge transfer, bioimaging, sensor, and surface-enhanced Raman scattering were briefly reviewed.

4. Hydrothermal route for cutting graphene sheets into blue-luminescent graphene quantum dots (Pan et al. 2010)

The article was published by Pan and other three authors from Shanghai University in China with C_{2017} of 229 (ranked fourth) and TC_{2017} of 1148 (ranked second). In this communication, Pan et al. reported the hydrothermal approach for cutting of graphene sheets into surface-functionalized graphene quantum dots, which is the first report on chemical preparation of functionalized graphene quantum dots with sub-10 nm sizes. Upon the oxidation by H_2SO_4 and HNO_3, graphene sheets were hydrothermally treated at 200 °C for 10 h to obtain graphene quantum dots. Graphene quantum dots had an average diameter of 9.6 nm and the height was 1–2 nm. Under UV irradiation, the blue luminescence at 430 nm was observed. The quantum yield of graphene quantum dots was 6.9%. The luminescence of graphene quantum dots depended on excitation wavelengths and pH values.

5. Nitrogen-doped graphene quantum dots with oxygen-rich functional groups (Li et al. 2012b)

The article was published by Li and other six authors from Beijing Institute of Technology in China, Tsinghua University in China, Case Western Reserve University in the USA with C_{2017} of 207 (ranked fifth) and TC_{2017} of 781 (ranked ninth). In this communication, Li et al. reported the first attempt of doping graphene quantum dots with nitrogen to effectively tune their intrinsic properties and explore new applications. Nitrogen-doped graphene quantum dots were prepared by an electrochemical approach using tetrabutylammonium perchlorate as the N source. The N/C ratio of N-doped graphene quantum dots was 4.3%. The nitrogen shifted the emission from green light to blue light, which was due to the relatively strong electron affinity of N atoms. N-doped graphene quantum dots supported on graphene sheets possessed superior electrocatalytic ability for oxygen reduction reaction.

6. Water-soluble fluorescent carbon quantum dots and photocatalyst design (Li et al. 2010)

The article was published by Li and other nine authors from Soochow University in China, Northeast Normal University in China, Centre of Super-Diamond and Advanced Films (COSDAF) in China with C_{2017} of 207 (ranked fifth) and TC_{2017} of 1016 (ranked fourth). In this communication, Li et al. developed a one-step alkali-assisted electrochemical fabrication of differently sized carbon dots to evidence the size-dependent photoluminescence and excellent upconversion luminescence. By changing the current densities, the size of carbon dots could be controlled (1.2–3.8 nm), in particular, after the separation of simple column chromatography. The emission of carbon dots shifted from 350 nm for 1.2 nm carbon dots to 800 nm for 3.8 nm carbon dots. Theses carbon dots possessed clear upconversion photoluminescence properties upon the excitation from 500 to 1000 nm. In addition, carbon dots could be fabricated with TiO_2 or SiO_2 for the photocatalytic decoloration of methylene blue.

7. Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis, and photovoltaic devices (Shen et al. 2012)

The article was published by Shen and other three authors from East China University of Science and Technology in China with C_{2017} of 189 (ranked seventh) and TC_{2017} of 817 (ranked eighth). This is another feature article, in which Shen et al. reviewed the recent developments in the preparation and applications of graphene quantum dots. It is again mistakenly categorized as an article in SCI-EXPANDED database. The synthesis of graphene quantum dots by top-down and bottom-up approaches was summarized. Optical properties, cytotoxicity, and other physical properties of graphene quantum dots were briefly introduced. The applications of graphene quantum dots in bioimaging, electrochemical biosensors, catalyst for the oxygen reduction reaction, and organic photovoltaic devices were reviewed in details. The outlook was made from the synthesis methods, surface engineering, fluorescence enhancement, and other analogs.

8. Graphene quantum dots derived from carbon fibers (Peng et al. 2012)

The article was published by Peng and other 15 authors from Nanjing University in China, Rice University in USA, Council for Scientific and Industrial Research (CSIR) in India, University of Texas MD Anderson Cancer Center in USA, Shinshu University in Japan, Ocean University of China in China, Baylor College of Medicine in USA with C_{2017} of 187 (ranked eighth) and TC_{2017} of 865 (ranked sixth). In this letter, Peng et al. reported the one-step wet chemical preparation of graphene quantum dots GQDs from carbon fibers with resin-rich surface. The new preparation protocol could tailor the photoluminescence of graphene quantum dots by changing reaction temperatures, which resulted in differently sized graphene quantum dots. The bandgap of graphene quantum dots was controlled by the particle size and the size-dependent emission was evidenced. The bioimaging capability of graphene quantum dots was demonstrated in human breast cancer cell T47D, where graphene quantum dots accumulated in the cytoplasm.

9. An electrochemical avenue to green-luminescent graphene quantum dots as potential electron-acceptors for photovoltaics (Li et al. 2011)

The article was published by Li and other six authors from Beijing Institute of Technology, Tsinghua University, Beijing Jiaotong University in China with C_{2017} of 173 (ranked ninth) and TC_{2017} of 753 (ranked tenth). In this letter, Li et al. reported a new electrochemical approach for direct preparation of functional graphene quantum dots of uniform size 3–5 nm. Graphene film was treated with O_2 plasma and used as the working electrode to produce graphene quantum dots. Graphene quantum dots emitted strong green luminescence (473 nm) and were stable during storage for months. Graphene quantum dots could be used as electron acceptor material in P3HT-based solar cell. Isc, Voc, FF, and PCE of P3HT-based solar cell were all enhanced by graphene quantum dots, highlighting the great potential of graphene quantum dots in photovoltaic devices.

10. Carbon dots for multiphoton bioimaging (Cao et al. 2007)

The article was published by Cao and other 11 authors from Clemson University in the USA with C_{2017} of 169 (ranked tenth) and TC_{2017} of 1035 (ranked third).

In this communication, Prof. Ya-Ping Sun and coworkers firstly discovered the two-photon luminescence property of carbon dots and achieved the multiphoton bioimaging in human cancer cells. Carbon dots were prepared by surface passivation with poly-(propionylethylenimine-co-ethylenimine) and the sizes were generally smaller than 5 nm. Carbon dots could be excited by 458 nm argon-ion laser for single-photon excitation and also by 800 nm femtosecond pulsed laser for two-photon excitation. Carbon dots were imaged in the cytoplasm of human breast cancer MCF-7 cells under two-photon luminescence microscopy, suggesting the potential of carbon dots for multiphoton bioimaging.

Research hotspots and their trends

The distribution of words in article titles, abstracts, author keywords, and *KeyWords Plus* can be informative when evaluating trends in research topics (Zhang et al. 2010b; Wang and Ho 2016). From the words in title, after excluding the name of carbon dots and graphene quantum dots and also the fluorescence-related words, which defined the fluorescent carbon nanoparticles, the most frequently used words are "synthesis, detection, imaging, sensing, sensitive, nitrogen-doped, selective, green, probe, ions, properties, facile, cells, applications, cell, acid, preparation, bioimaging, sensor, and determination". "Synthesis," held the total number of 540 articles, is the most used word in title. As a new category of fluorescent materials, the major effort has been dedicated to the synthesis of fluorescent carbon nanoparticles. Synthesis is also listed among the most frequent words in article abstract, author keywords, and *KeyWords Plus*. Following synthesis is "detection," which highlights the applications of fluorescent carbon nanoparticles in the analysis of substances. In this application, the fluorescence intensity would change upon the stimulation of analytes and the correlation ship is used for identification or quantification. Detection is also listed in the popular words in abstract, author keywords, and *KeyWords Plus*. The third frequent one is imaging, that has a total number of 306 articles. Fluorescence recording of fluorescent carbon nanoparticles in cells is commonly used to demonstrate the potential in imaging applications. A few of these articles imaged carbon nanoparticles in animals. Beyond the analysis and imaging applications, the author keyword "photocatalysis" indicated that the catalytic applications of fluorescent carbon nanoparticles have attracted great interest. Other interesting words are "cytotoxicity" and "electron," which suggest the importance of low toxicity and the applications in electronic related areas.

The results of our keyword analyses provide information about the main and possible research foci as each word cluster comprised several supporting words. Thus, the possible main research foci in fluorescent carbon nanoparticles research are:

1. Analysis: This focus is supported by word cluster of "analysis, concentration, detection, determination, ions, probe, selective, sensing, sensitive, and sensor", holding a total number of 2323 articles. Analysis is an important issue and could be applied in many areas. The annual article number of fluorescent carbon nanoparticles for analysis increased sharply after 2011 (Fig. 5). One highly cited article concerned the detection of Fe^{3+} by carbon dots (Zhu et al. 2013). The fluorescence quenching/enhancing of fluorescent carbon nanoparticles provided ideal responsive signals for analysis. In addition, the experimental procedures are easier in solution than bioimaging experiments. Therefore, many researches dedicated in the analysis applications of fluorescent carbon nanoparticles.
2. Imaging applications: This focus is supported by the word cluster of "bioimaging, cell, imaging, in vivo, probe, sensing, and sensor", which held a total number of 2287 articles. Imaging is the initial purpose of developing fluorescent carbon nanoparticles. All the highly cited articles talk about the

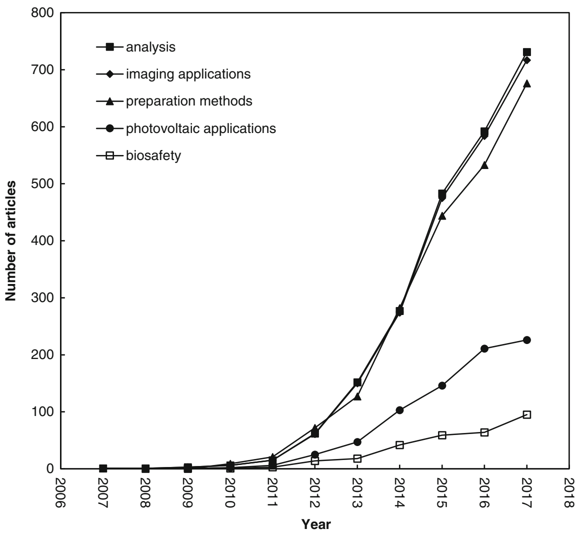

Fig. 5 Growth trends of main research focuses during 1991–2017

imaging applications. Imaging applications published similar numbers of articles to those of analysis. In the beginning of carbon dots, they were designed for bioimaging applications to overcome the toxicity drawback of semiconductor quantum dots. In 2006, carbon dots were imaged in bacteria and cells (Sun et al. 2006). The two-photon imaging in cells was achieved in 2007 (Cao et al. 2007) and the imaging in animals was established in 2009 (Yang et al. 2009a, b). Looking into these imaging applications, most of them were performed on microorganisms and mammalian cells. There are fewer ethics issues for such studies and the cultivation conditions are simpler. In future studies, in vivo imaging applications are highly recommended to push fluorescent carbon nanoparticles for clinical uses.

3. Preparation methods: This focus is supported by the word cluster of "synthesis, nitrogen-doped, green, facile, preparation, method, yield, hydrothermal, simple, and facile" with a total number of 2165 articles. Seven of the eight highly cited articles (excluding the two feature articles) developed new methods for the preparation of fluorescent carbon nanoparticles. Interestingly, nitrogen doping is a hot method in the modification of fluorescent carbon nanoparticles. In the highly cited article by Li et al. (2012a, b), nitrogen-doped graphene quantum dots were prepared for catalytic applications. Generally, each article on fluorescent carbon nanoparticles is involved with preparation protocol and many of them dedicated to improve or modify the preparation methods. There are many methods reported, including surface functionalization of small particles, hydrothermal carbonization, acidic/basic carbonization, hydrothermal cutting, and doping with other elements. The main aims of preparation methods studies are higher product yield and larger scale, higher quantum yield and more stable fluorescence, red and infrared emissions, and proper surface chemistry for diverse applications.
4. Photovoltaic applications: Photovoltaic applications have one supporting word "electron." The energy problem is currently a very hot topic in material science. The potential of fluorescent carbon nanoparticles in converting photons into electrons would extend their applications and importance. The electronic properties of fluorescent carbon nanoparticles are concerned by the community and more related articles are published in recent years. Among the highly cited articles, Li et al. (2011) used graphene quantum dots in photovoltaic devices. In future, fluorescent carbon nanoparticle-based solar cells are the main pursuits for practical uses.
5. Biosafety: The biosafety issue is supported by the word "cytotoxicity." The annual publication on cytotoxicity of fluorescent carbon nanoparticles increased to 95 articles in 2017. The toxicity issue should be thoroughly investigated to guarantee the safe applications of fluorescent carbon nanoparticles. The good biocompatibility of fluorescent carbon nanoparticles is the major advantage over semiconductor quantum dots. Just as the imaging applications, most studies focused on the cytotoxicity of carbon nanoparticles. Cell viability is the most used technique to preliminarily demonstrate the low toxicity. The in vivo evaluations are scarce, which should be enforced in the future. More systematic evaluations and mechanism investigations of the toxicity of fluorescent carbon nanoparticles are expected.

Conclusions

In fluorescent carbon nanoparticle field, 2933 documents in eight document types were found in SCI-

EXPANDED from 2006 to 2017. English was the dominant language. A sharply yearly number of articles increased was found after 2011. The most cited and also the most impact articles were published in 2006. Top three productive journals including *RSC Advances*, *Nanoscale*, and *Sensors and Actuators B-Chemical* were listed in Web of Science category of multidisciplinary chemistry. China dominated six publication indicators such as the total number of articles, country independent articles, internationally collaborative articles, first author articles, corresponding author articles, and single-author followed by India. It is surprising from publication performance of University of Chinese Academy of Sciences in China which ranked second in inter-institutionally collaborative articles and third in total articles but much less number of institute independent, first author, and corresponding author articles. The top ten highly cited articles with total citations from Web of Science Core Collection since publication to the end of 2017 were the same as the top ten high impact articles with total citations in 2017 only. Analysis, imaging applications, and preparation methods were three hotspots in fluorescent carbon nanoparticle field.

Compliance with ethical standards

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

References

Atabaev TS (2018) Doped carbon dots for sensing and bioimaging applications: a minireview. Nanomaterials, 8, article number: 342

Baker SN, Baker GA (2010) Luminescent carbon nanodots: emergent nanolights. Angew Chem Int Edit 49:6726–6744

Cao L, Wang X, Meziani MJ, Lu F, Wang H, Luo PG, Lin Y, Harruff BA, Veca LM, Murray D, Xie SY, Sun YP (2007) () Carbon dots for multiphoton bioimaging. J Am Chem Soc 129:11318–11319

Cao L, Meziani MJ, Sahu S, Sun YP (2013) Photoluminescence properties of graphene versus other carbon nanomaterials. Accounts Chem Res 46:171–180

Chaudhary S, Umar A, Bhasin KK, Singh S (2017) Applications of carbon dots in nanomedicine. J Biomed Nanotechnol 13: 591–637

Chiu WT, Ho YS (2005) Bibliometric analysis of homeopathy research during the period of 1991 to 2003. Scientometrics 63:3–23

Chiu WT, Ho YS (2007) Bibliometric analysis of tsunami research. Scientometrics 73:3–17

Chuang KY, Ho YS (2014) A bibliometric analysis on top-cited articles in pain research. Pain Med 15:732–744

Chuang KY, Huang YL, Ho YS (2007) A bibliometric and citation analysis of stroke-related research in Taiwan. Scientometrics 72:201–212

Chuang KY, Wang MH, Ho YS (2011) High-impact papers presented in the subject category of water resources in the essential science indicators database of the Institute for Scientific Information. Scientometrics 87:551–562

Essner JB, Baker GA (2017) The emerging roles of carbon dots in solar photovoltaics: a critical review. Environ Sci-Nano 4: 1216–1263

Fu HZ, Wang MH, Ho YS (2012) The most frequently cited adsorption research articles in the Science Citation Index (expanded). J Colloid Interf Sci 379:148–156

Garfield E (1990) KeyWords Plus: ISI's breakthrough retrieval method. Part 1. Expanding your searching power on current contents on diskette. Current Contents 32:5–9

Han JS, Ho YS (2011) Global trends and performances of acupuncture research. Neurosci Biobehav R 35:680–687

Ho YS (2012) Top-cited articles in chemical engineering in Science Citation Index expanded: a bibliometric analysis. Chinese J Chem Eng 20:478–488

Ho YS (2013) The top-cited research works in the Science Citation Index expanded. Scientometrics 94:1297–1312

Ho YS (2014) A bibliometric analysis of highly cited articles in materials science. Curr Sci India 107:1565–1572

Ho YS, Fu HZ (2016) Mapping of metal-organic frameworks publications: a bibliometric analysis. Inorg Chem Commun 73:174–182

Ho YS, Hartley J (2016) Classic articles published by American scientists (1900-2014): a bibliometric analysis. Curr Sci India 111:1156–1165

Ho YS, Satoh H, Lin SY (2010) Japanese lung cancer research trends and performance in Science Citation Index. Intern Med J 49:2219–2228

Ho YS, Siu E, Chuang KY (2016) A bibliometric analysis of dengue-related publications in the Science Citation Index expanded. Future Virol 11:631–648

Hsieh WH, Chiu WT, Lee YS et al (2004) Bibliometric analysis of patent ductus arteriosus treatments. Scientometrics 60:205–215

Huang P, Lin J, Wang XS, Wang Z, Zhang C, He M, Wang K, Chen F, Li Z, Shen G, Cui D, Chen X (2012) Light-triggered theranostics based on photosensitizer-conjugated carbon dots for simultaneous enhanced-fluorescence imaging and photodynamic therapy. Adv Mater 24:5104–5110

Hutton GAM, Martindale BCM, Reisner E (2017) Carbon dots as photosensitisers for solar-driven catalysis. Chem Soc Rev 46: 6111–6123

Kostoff RN, Tshiteya R, Pfeil KM, Humenik JA (2002) Electrochemical power text mining using bibliometrics and database tomography. J Power Sources 110:163–176

Kostoff RN, Stump JA, Johnson D, Murday JS, Lau CGY, Tolles WM (2006) The structure and infrastructure of the global nanotechnology literature. J Nanopart Res 8:301–321

Kostoff RN, Koytcheff RG, Lau CGY (2007a) Structure of the nanoscience and nanotechnology instrumentation literature. Curr Nanosci 3:135–154

Kostoff RN, Koytcheff RG, Lau CGY (2007b) Technical structure of the global nanoscience and nanotechnology literature. J Nanopart Res 9:701–724
LeCroy GE, Yang ST, Yang F et al (2016) Functionalized carbon nanoparticles: syntheses and applications in optical bioimaging and energy conversion. Coordin Chem Rev 320:66–81
Lee YC, Chen CM, Tsai XT (2016) Visualizing the knowledge domain of nanoparticle drug delivery technologies: a scientometric review. Appl Sci-Basel 6:11
Li Z, Ho YS (2008) Use of citation per publication as an indicator to evaluate contingent valuation research. Scientometrics 75: 97–110
Li JF, Zhang YH, Wang XS et al (2009) Bibliometric analysis of atmospheric simulation trends in meteorology and atmospheric science journals. Croat Chem Acta 82:695–705
Li HT, He XD, Kang ZH, Huang H, Liu Y, Liu J, Lian S, CHA T, Yang X, Lee ST (2010) Water-soluble fluorescent carbon quantum dots and photocatalyst design. Angew Chem Int Edit 49:4430–4434
Li Y, Hu Y, Zhao Y, Shi G, Deng L, Hou Y, Qu L (2011) An electrochemical avenue to green-luminescent graphene quantum dots as potential electron-acceptors for photovoltaics. Adv Mater Interfaces 23:776–1043
Li HT, Kang ZH, Liu Y, Lee ST (2012a) Carbon nanodots: synthesis, properties and applications. J Mater Chem A 22: 24230–24253
Li Y, Zhao Y, Cheng HH, Hu Y, Shi G, Dai L, Qu L (2012b) Nitrogen-doped graphene quantum dots with oxygen-rich functional groups. J Am Chem Soc 134:15–18
Lin CL, Ho YS (2015) A bibliometric analysis of publications on pluripotent stem cell research. Cell J 17:59–70
Liu P, Chen BL, Liu K, Xie H (2016) Magnetic nanoparticles research: a scientometric analysis of development trends and research fronts. Scientometrics 108:1591–1602
Luo PJG, Sahu S, Yang ST et al (2013) Carbon "quantum" dots for optical bioimaging. J Mater Chem B 1:2116–2127
Luo PJG, Yang F, Yang ST et al (2014) Carbon-based quantum dots for fluorescence imaging of cells and tissues. RSC Adv 4:10791–10807
Pan DY, Zhang JC, Li Z, Wu M (2010) Hydrothermal route for cutting graphene sheets into blue-luminescent graphene quantum dots. Adv Mater 22:734–738
Peng J, Gao W, Gupta BK, Liu Z, Romero-Aburto R, Ge L, Song L, Alemany LB, Zhan X, Gao G, Vithayathil SA, Kaipparettu BA, Marti AA, Hayashi T, Zhu JJ, Ajayan PM (2012) Graphene quantum dots derived from carbon fibers. Nano Lett 12:844–849
Peng ZL, Han X, Li SH, al-Youbi AO, Bashammakh AS, el-Shahawi MS, Leblanc RM (2017) Carbon dots: biomacromolecule interaction, bioimaging and nanomedicine. Coordin Chem Rev 343:256–277
Pouris A, Ho YS (2016) A bibliometric analysis of research on Ebola in Science Citation Index expanded. S Afr J Sci 112: 83–88
Shen JH, Zhu YH, Yang XL, Li C (2012) Graphene quantum dots: emergent nanolights for bioimaging, sensors, catalysis and photovoltaic devices. Bulg Chem Commun 48:3686–3699
Sun YP, Zhou B, Lin Y, Wang W, Fernando KAS, Pathak P, Meziani MJ, Harruff BA, Wang X, Wang H, Luo PG, Yang H, Kose ME, Chen B, Veca LM, Xie SY (2006) Quantum-sized carbon dots for bright and colorful photoluminescence. J Am Chem Soc 128(24):7756–7757
Sun YP, Wang X, Lu FS, Cao L, Meziani MJ, Luo PG, Gu L, Veca LM (2008) Doped carbon nanoparticles as a new platform for highly photoluminescent dots. J Phys Chem C 112:18295–18298
Tanaka H, Ho YS (2011) Global trends and performances of desalination research *Desalin*. Water Treat 25:1–12
Tang YL, Xin HJ, Yang F et al (2018) A historical review and bibliometric analysis of nanoparticles toxicity on algae. J Nanopart Res, 20, article number: 92
Wang MH, Ho YS (2011) Research articles and publication trends in environmental sciences from 1998 to 2009. Archives of Environmental Science 5:1–10
Wang CC, Ho YS (2016) Research trend of metal-organic frameworks: a bibliometric analysis. Scientometrics 109:481–513
Wang MH, Fu HZ, Ho YS (2011) Comparison of universities' scientific performance using bibliometric indicators. Malays J Libr Inf Sc 16:1–19
Wang M, Chen J, Liu CG et al (2017) A graphene quantum dots-hypochlorite hybrid system for the quantitative fluorescent determination of total antioxidant capacity. Small, 13, article number: UNSP 1700709
Wang ZJ, Zhang TC, Huang FY, Wang Z (2018) The reproductive and developmental toxicity of nanoparticles: a bibliometric analysis. Toxicol Ind Health 34:169–177
Yang ST, Cao L, Luo PGJ et al (2009a) Carbon dots for optical imaging in vivo. J Am Chem Soc 131:11308–14263
Yang ST, Wang X, Wang HF, Lu F, Luo PG, Cao L, Meziani MJ, Liu JH, Liu Y, Chen M, Huang Y, Sun YP (2009b) Carbon dots as nontoxic and high-performance fluorescence imaging agents. J Phys Chem C 113:18110–18114
Zhang L, Wang MH, Hu J, Ho YS (2010a) A review of published wetland research, 1991-2008: ecological engineering and ecosystem restoration. Ecol Eng 36:973–980
Zhang GF, Xie SD, Ho YS (2010b) A bibliometric analysis of world volatile organic compounds research trends. Scientometrics 83:477–492
Zheng MS, Fu HZ, Ho YS (2017) Research trends and hotspots related to ammonia oxidation based on bibliometric analysis. Environ Sci Pollut R 24:20409–20421
Zhu SJ, Meng QN, Wang L, Zhang J, Song Y, Jin H, Zhang K, Sun H, Wang H, Yang B (2013) Highly photoluminescent carbon dots for multicolor patterning, sensors, and bioimaging. Angew Chem Int Edit 52:3953–3957