A historical review of aggregation-induced emission from 2001 to 2020: A bibliometric analysis

Qiming Xia1 | Yiyin Zhang1 | Yiling Li1 | Yirun Li1 | Yixuan Li1 | Zhe Feng2 | Xiaoxiao Fan1,2 | Jun Qian1,2 | Hui Lin1,3

1 Department of General Surgery, Sir Run Run Shaw Hospital, School of Medicine, Zhejiang University, Zhejiang Province, Hangzhou, P. R. China
2 State Key Laboratory of Modern Optical Instrumentations, Centre for Optical and Electromagnetic Research, College of Optical Science and Engineering, International Research Center for Advanced Photonics, Zhejiang University, Hangzhou, P. R. China
3 College of Biomedical Engineering and Instrument Science, Zhejiang University, Hangzhou, P. R. China

Abstract

Aggregation-induced emission (AIE) is a photophysical phenomenon that a certain group of luminescent materials that become highly luminous when aggregated in a bad solvent or solid state. This year is the 20th anniversary since the AIE concept firstly proposed in 2001. Many advanced applications were gradually being explored, covering optics, electronics, energy, and bioscience and so on. At present, bibliometrics can enlighten the researchers with comprehensive sights of the achievements and trends of a specific field, which is critical for academic investigations. Herein, we presented a general bibliometric overview of AIE covering 20 years of evolution. With the assistance of Web of Science Core Collection database and several bibliometric software tools, the annual publication and citation, most influential countries/regions, most contributing authors, journals and institutions, second near-infrared (NIR-II) related hotspots, as well as the forecast of frontiers were demonstrated and systematically analyzed. This study summarizes the current research status in AIE research field and provides a reference for future research directions.

KEYWORDS
aggregation-induced emission (AIE), bibliometric analysis, research trend, second near-infrared (NIR-II)

1 INTRODUCTION

Aggregation-induced emission (AIE) is an atypical photophysical phenomenon in which nonemissive luminogens are elicited to emit effectively in the aggregate formation.\(^1\) The concept of AIE was first proposed by Tang Ben Zhong’s research team in 2001,\(^2\) which effectively breaks the barrier caused by traditional aggregation-caused quenching materials,\(^{1,3}\) and brings about a vast landscape of its applications. With years of explorations on the AIE phenomena, the restriction of intramolecular motions (RIM) has been identified as the working mechanism of AIE.\(^4\) The clear understanding of structure–property relationships of AIEgens facilitates the development of materials science and related applications. To date, AIEgens have widely applied in area of bioimaging,\(^5,6\) AIE-based chemosensing...
systems,\textsuperscript{[7]} OLED devices,\textsuperscript{[8]} circularly polarized luminescence systems,\textsuperscript{[9]} optical waveguides,\textsuperscript{[10]} and liquid crystal displays.\textsuperscript{[11]}

Unlike systemic reviews or scooping reviews, bibliometric analysis is a scientific method that investigates publications using statistical methods and mapping approaches aimed to prognosticate the developing trends of specific areas.\textsuperscript{[12]} It is a newfangled discipline that extracts mathematical laws in a great deal of literature.\textsuperscript{[13]} It is capable of not only evaluating the contributions of countries/regions, authors, journals, and institutions but also disclosing the hotspots and development trends of specific research fields.\textsuperscript{[14]}

In the field of AIE research, many research papers and reviews have been published over the past two decades, however, few studies have been conducted to analyze and investigate the publication studies. Herein, we provided a literature overview and analysis of the AIE researches based on the data collected from the Web of Science Core Collection, and performed a historically review of the AIE development at 20th anniversary since the proposal of this concept. The indexes of publication and citation including annual growth, most productive countries/regions, most contributing authors, journals, and institutions were presented and visualized by several sorts of bibliometric software. We listed the 30 most academically influential AIE articles in the field by sorting the number of citations. We also perform a keyword co-occurrence analysis to show the research hotspots of AIE in China and other countries. In addition, AIE studies on the field of second near-infrared (NIR-II) fluorescence imaging using AIE probes particularly attracted our attention and were described in detail. Last but not least, we especially analyzed the researches published within 1 year and attempted to provide potential prospects for the future research in AIE field.

2 | ANALYSIS METHODS

2.1 | Materials

We performed a literature search from the Web of Science Core Collection database on August 10, 2021. The search queries were set to obtain the publications between 2001 and 2020: TS = aggregation-induced emission. The criteria for the collected data included the year of publication, institution, country, authorship, abstract, keyword, citation, and references. After duplicates and irrelevant papers were removed, a total of 8758 publications were retrieved and analyzed.

2.2 | Data analysis

Citespace 5.8.R1, Vosviewer 1.6.17, the R bibliometrix package v3.1.4 and Carrot\textsuperscript{2} application were used in bibliometric analysis. The top six countries and regions and the top eight authors were shown by Citespace. The collaborative network of the countries and regions, authors and journals were visualized by Vosviewer. Also, the keyword density maps of AIE field of China and other countries were generated by Vosviewer. The hotspot treemap was produced by the Carrot\textsuperscript{2} application, which is a programming library for clustering text. The three-field plot and the bibliometric geographic map were created by the R bibliometrix package. Calculation and graphing of publications and citations were performed by Graphpad Prism 8.3.0.

3 | AN OVERVIEW OF AIE STUDIES THROUGH BIBLIOMETRIC ANALYSIS

3.1 | Growth of publications and citations

Since the unique photophysical phenomenon, which is known as AIE, was proposed by Tang’s team in 2001, the interesting luminescence properties of AIEgens have attracted a great deal of attention. A total of 8884 documents was finally collected from Web of Science Core Collection database by our searching strategy, including 8089 articles, 634 reviews, and 161 other types of studies. These documents have received 251,203 times of citations until August 10, 2021, with an average citation of 28.3 times per item. The numbers of publications and citations were presented in Figure 1A. The growth of publications was accelerated distinctly since 2010, which indicated the concept was gradually accepted by more and more researchers from that on (Figure 1A). In 2020 alone, there were 1768 publications and 60,793 citations in the AIE field, which showed strong influence in the research community. As AIE was firstly proposed by Chinese researchers, we further assessed whether the AIE phenomenon aroused interest from international scholars. Then we divided the documents into two categories, which were documents from China and outside China. Publications and citations of those two categories were both significantly growing over time (Figure 1B,C). Because of the fact that the publications and citations were relatively few in the very first years, we mainly analyzed the data starting from 2007 to 2020. It was found that even though the numbers of publications and citations increased rapidly year by year, the proportion of publications and citations from China showed a decreased trend (Figure 1D). This phenomenon was induced by multiple factors. One reason might be the increasingly global collaborations and communications. A series of international AIE-relevant academic conferences, such as the “3rd International Symposium on Aggregation-Induced Emission” held in Singapore in 2017, promoted the collaborations and enhanced international communications in this field. The excellent performance of AIE materials encouraged more scientists outside China dedicated to this area. Also in 2016, “Nature” listed AIE-dots as one of the four most concerned fluorescent dots.\textsuperscript{[15]} Reports of influential journals such as “Nature” undoubtedly boosted the popularity and visibility of AIE researches. The results demonstrated the new concept proposed by Chinese scientists was increasingly investigated in the regions outside China. Following that, we further compared AIEgens with other fluorescent probes. Herein, rare earth-doped nanoparticles, another fluorescent material that received great attention, were selected for comparison. Rare earths are a family of 17 elements that exhibit pronounced chemical similarities and varied electronic properties.\textsuperscript{[16]} Because of their 4f electron configurations, rare earth-doped nanoparticles have large Stokes/anti-Stokes shifts, long luminescent lifetimes and good photostability.\textsuperscript{[17]} Annual literature were collected from 2008 to 2020 based on the search term (“AIE” AND “fluorescent probe”) and (“rare earth” AND “fluorescent probe”). From the data presented in the
form of a bar diagram illustrated in Figure 1E, publication number of rare earth-doped nanoparticles remained stable, which indicated rare earth-fluorescent probes maintained a certain degree of heat. However, the annual publication number of AIE materials in the optical field increased rapidly. The annual publication number of AIE fluorescent probes was comparable to that of rare earth-doped nanoparticles in 2015, while the publication number of AIE fluorescent probes was twice that of rare earth-doped nanoparticles in 2020.

3.2 Most productive countries/regions and cooperation network

Ever since the AIE phenomenon appeared in front of the scientific vision, many countries/regions made devotion to this field. Here, we exhibited the top six most productive and weighty countries/regions according to the indexes of publications, citations, centrality and link strength. As illustrated in Figure 2A, China dominated the ranking with a total of 6139 publications, 221,415 citations, and 0.44 centrality, and followed by India (898 publications, 17,770 citations, and 0.27 centrality). Notably, the studies from Singapore manifested the highest citations per publication (67.04 times per publication), which indicated that studies from Singapore commonly aroused great interest of other researchers. Besides, an academic correlation network was also shown in Figure 2B using the “link strength” indicator. From the network, China held the strongest global partnership (71,434 total link strength). To make the connections among countries/regions more tangible, the data was visualized on a
FIGURE 2  Summaries of the most productive countries/regions and cooperation networks in AIE research. (A) The top six most productive countries in the aggregation-induced emission (AIE) field. (B) Network visualization map of international research collaboration on AIE. (C) Global collaboration in AIE research among nations. (D) Global collaboration in AIE research among nations from 2001 to 2010. (E) Global collaboration in AIE research among nations from 2011 to 2020. The thickness of the connecting lines represented the strength of research collaboration. The geographic map (Figure 2C). The thickness of the connecting lines represented the strength of research collaboration. The collaboration between China and Singapore was the closest among all, and the collaboration between China and United States was secondly active. To further exhibit the development of global collaborations, we visualized the difference of collaboration networks between in the period of 2001 and 2010 and in the period of 2011 and 2020. The number of connecting lines obviously increased, and lines became thicker in the period of 2011 and 2020 (Figure 2D,E). Overall, it was
### TABLE 1: The top six productive and influential countries between 2001 and 2020

| Rank | Country    | Records | Total citations | Centrality | Citations per item | Total link strength |
|------|------------|---------|-----------------|------------|--------------------|--------------------|
| 1    | China      | 6139    | 221,415         | 0.44       | 36.07              | 71,434             |
| 2    | India      | 898     | 17,770          | 0.27       | 19.79              | 17,376             |
| 3    | Japan      | 493     | 15,295          | 0.05       | 31.02              | 11,457             |
| 4    | USA        | 462     | 22,368          | 0.14       | 48.42              | 11,853             |
| 5    | Singapore  | 358     | 24,000          | 0.03       | 67.04              | 18,028             |
| 6    | South Korea| 279     | 9,332           | 0.11       | 33.45              | 6218               |

### TABLE 2: The top 15 most contributing authors in aggregation-induced emission (AIE) field between 2001 and 2020

| Rank | Author                        | Articles | Citations | Average citations | Total link strength |
|------|-------------------------------|----------|-----------|-------------------|---------------------|
| 1    | Tang Ben Zhong                | 975      | 72,649    | 74.51             | 105,813             |
| 2    | Lam Jacky Wing Yip            | 340      | 40,337    | 118.64            | 55,013              |
| 3    | Liu Bin                       | 242      | 16,509    | 68.22             | 25,799              |
| 4    | Qin Anjun                     | 235      | 14,673    | 62.44             | 25,877              |
| 5    | Zhao Zujin                    | 187      | 9,283     | 49.64             | 23,998              |
| 6    | Wei Yen                       | 186      | 6,953     | 37.38             | 34,852              |
| 7    | Zhang Xiaoyong                | 173      | 6,577     | 38.02             | 32,646              |
| 8    | Kowk Ryan Tsz Kin            | 171      | 6,577     | 38.46             | 23,381              |
| 9    | Li Zhen                       | 128      | 8,080     | 68.75             | 16,045              |
| 10   | Liu Meiying                   | 122      | 5,181     | 42.47             | 25,767              |
| 11   | Chi Zhenguco                  | 101      | 9,634     | 95.39             | 15,359              |
| 12   | Zhang Xiqi                    | 98       | 8,229     | 83.97             | 23,029              |
| 13   | Lu Ping                       | 93       | 8,069     | 86.76             | 13,712              |
| 14   | Hong Yuning                   | 84       | 15,116    | 179.95            | 17,534              |
| 15   | Hu Rongrong                   | 81       | 6,925     | 85.49             | 10,681              |

### 3.3 Most contributing authors and collaborative network

A total of 15,898 authors published their papers exclusively or collaboratively on AIE topics from 2001 to 2020. To utterly present the most contributing authors in this area, some of the most influential and contributing authors in the AIE field are listed in Table 2 and Figure 3A. It is widely known that the AIE phenomenon was firstly reported by Tang Ben Zhong’s group in 2001. From that on, his group dedicated to this emerging field and published 975 articles with a total of 72,649 citations until Dec 31, 2020. His work covered various aspects of AIE phenomena which were composed of the decipherment of AIE mechanism,[18] the synthesis of a broad range of AIEgens,[19] and the illustration of a variety of applications.[20] Other productive authors like “Lam Jacky Wing Yip” (340 publications), “Liu Bin” (242 publications), “Qin Anjun” (235 publications), “Zhao Zujin” (187 publications), “Wei Yen” (186 publications), “Zhang Xiaoyong” (173 publications) and “Kowk Ryan Tsz Kin” (171 publications) and so on. Others also made great contributions to this area, and “Liu Bin” from Singapore was the most productive author in the regions outside China. As shown in Figure 3B, an international collaborative network indicated the “link strength” among all authors, which suggested the tightness of collaboration between 2 authors. In addition, the color stood for the active period of a certain author. The authors with purple nodes, “Zhang Xiqi” for instance, were active in the AIE field at a relatively earlier time, meanwhile authors with yellowish nodes, such as “Zhang Pengfei,” were moving actively in the AIE field recently. Intriguingly, the three main clusters named “Tang Ben Zhong,” “Liu Bin” and “Wei Yen” respectively, were relatively highlighting and independent. Besides, the collaborations among the three relatively independent clusters were also very close. It was logically reasonable that the more independent clusters could inject new vitality into the AIE field. For the purpose of facilitating and promoting possible cooperation between various authors in the AIE field, a three-field plot of institutions, authors and most related fields was generated using the R bibliometrix package (Figure 4). Of note, one of the limitations in bibliometric analysis is that this method focuses on the researchers. If the analysis were based on the research groups rather than researchers, the conclusions would be more meaningful, because most of the authors from the same group contribute to the same paper.
3.4 Most relevant and leading journals and institutions

By Dec 31, 2020, over 500 various kinds of journals have published articles on the topic of AIE. Here we listed the top 10 most relevant journals (Table 3) and visualized the journal-citation network (Figure 5). The most relevant journal is “Journal of Materials Chemistry C” with 528 publications and 16,495 citations, followed by “Dyes and Pigments” (443 publications and 6281 citations), “Chemical Communications” (416 publications and 29,121 citations), and so forth. The journals with purple nodes, “Chemical Communications” for example, were tended to be active at an earlier period, while journals with yellowish nodes, such as “Angewandte Chemie-International Edition” and “ACS Nano,” becoming more active recently (Figure 5).
On the aspect of institutions, Hong Kong University of Science and Technology was the most copious institution in this field, contributing 1137 publications and a total of 74,854 citations (Table 4). Chinese Academy of Sciences (1052 publications and 39,212 citations), South China University of Technology (619 publications and 15,914 citations), Jilin University (538 publications and 21,359 citations), and Zhejiang University (374 publications and 33,660 citations) were ranked second to the fifth position on the list. It should be emphasized here that we analyzed all the institution addresses rather than the first institution addresses. The average citation per item of Zhejiang University is 90.00 ranking the first according to this index, even though it ranked at the fifth position based on output. Likewise, in order to straighten out relations among institutions, authors, and most related journals, a three-field plot of the top 10 productive authors is produced by the R bibliometrix package (Figure 6). Correspondingly, authors from other countries are analyzed according to their countries and the most related journals (Figure 7).

### 3.5 Most cited papers

The progress of current scientific research always makes breakthroughs on the basis of the papers of the predecessors, which would be reflected in the form of references. Therefore, the number of citations was an important index to assess the influence of a certain research and was able to measure the importance of the work in the academic community. Herein, we listed the top 30 most cited papers, including 20 reviews, eight articles, and two communications (Table 5). The most cited paper (4339 citations) was an article entitled “Aggregation-induced emission of 1-methyl-1,2,3,4,5-pentaphenylsilole”
FIGURE 5  Co-occurrence network and time evolution of journals in the aggregation-induced emission (AIE) field. Node size was based on the publication number; color was used to indicate the average publication year.

TABLE 4  The top 10 active institutions in aggregation-induced emission (AIE) research field between 2001 and 2020

| Rank | Institution                                         | Publications | Citations | Average citations | Total link strength |
|------|-----------------------------------------------------|--------------|-----------|-------------------|---------------------|
| 1    | Hong Kong University of Science and Technology      | 1137         | 74,854    | 72.25             | 112,113             |
| 2    | Chinese Academy of Sciences                         | 1052         | 39,212    | 46.30             | 50,914              |
| 3    | South China University of Technology                | 619          | 15,914    | 25.71             | 44,215              |
| 4    | Jilin University                                    | 538          | 21,359    | 39.70             | 29,208              |
| 5    | Zhejiang University                                 | 374          | 33,660    | 90.00             | 42,225              |
| 6    | National University of Singapore                    | 310          | 20,764    | 66.98             | 29,857              |
| 7    | HKUST Shenzhen Research Institute                   | 254          | 11,500    | 36.51             | 21,137              |
| 8    | Wuhan University                                    | 235          | 12,384    | 56.55             | 17,568              |
| 9    | Sun Yat-sen University                              | 219          | 12,384    | 56.55             | 17,568              |
| 10   |                                                    |              |           |                   |                     |

(https://doi.org/10.1039/b105159h) by Luo et al. and published on “Chemical Communications” in 2001. This article was the cornerstone and linchpin of the AIE field as the conception of “AIE” was primarily proposed by Tang Ben Zhong’s research team.[23] The paper reported a silole compound 1-methyl-1,2,3,4,5-pentaphenylsilole whose fluorescence intensity was significantly enhanced when in the aggregation status rather than in solution status, which stimulated the new molecular design of AIE organics and polymers. The paper with the highest average citation per year (542.86 times per year) was a systematic review titled “Aggregation-induced emission: together we shine, united we soar!” (https://doi.org/10.1021/acs.chemrev.5b00263) in “Chemical Reviews” in 2015.[1] The review elaborated on the mechanism of AIE with different kinds of new AIEgens derived from the restriction of RIM theory, and innovative technological or biological applications of the AIEgens. Broadly speaking, we could recognize that the development of novel AIEgens attracted the paramount attention of researchers (Table 5).

3.6  | Keywords co-occurrence network analysis

Keywords could represent the core ideas of articles to some extent. It could also help to provide an overview of the research trends by analyzing keywords. Hence, with the intention of comprehending the research trends of AIE, we utilized VOSviewer to generate a knowledge network of keyword co-occurrence. Moreover, to uncover the difference of research scope between China and the regions outside China, we analyzed the keywords respectively. Figure 8A exhibited 100 keywords co-occurrence spectrum of China which occurred over 30 times within titles and abstracts in all papers, and the terms were categorized into three clusters. The largest cluster was stained in red, which was closely relevant to the underlying mechanisms of AIE phenomena. Keywords such as “fluorescence,” “enhanced emission,” “intramolecular charge-transfer,” “photoluminescence,” “solid-state,” “luminogens,” “electroluminescence,” “emitters,” and “mechanochromic luminescence” were identified.
as basal elements in the red cluster. Besides, the green cluster encompassed keywords like “organic nanoparticles,” “quantum dots,” “photodynamic therapy,” “in-vivo,” “cells,” “drug-delivery,” “cancer,” “in-vitro,” and “bioimaging.” This cluster mainly accounted for the application of AIE materials in biological or medical field. Likewise, the green cluster mainly focused on the field of the engineering and amelioration of AIEgens, which was formed from keywords like “enhancement,” “tetrphenylethylene,” “sensors,” “chemosensors,” “chemistry,” “turn-on,” “aqueous-solution,” “ions,” “metal nanoparticles,” and “gold nanoparticles.”
## Table 5
The thirty most cited aggregation-induced emission (AIE) documents sorted by total citation between 2001 and 2020

| Rank | Title                                                                 | Authors     | Journal                          | Year | Total citations | Average citations per year | Article type | DOI                      |
|------|-----------------------------------------------------------------------|-------------|----------------------------------|------|-----------------|-----------------------------|--------------|--------------------------|
| 1    | Aggregation-induced emission of 1-methyl-1,2,3,4,5-pentaphenylsilole | Luo et al.  | Chemical Communications           | 2001 | 4339            | 206.62                      | Article      | 10.1039/b105159h          |
| 2    | Aggregation-induced emission                                          | Hong et al. | Chemical Society Reviews          | 2011 | 3964            | 360.36                      | Review       | 10.1039/c1cs151113d       |
| 3    | Aggregation-Induced Emission: Together We Shine, United We Soar!      | Mei et al.  | Chemical Reviews                  | 2015 | 3800            | 542.86                      | Review       | 10.1021/acs.chemrev.5b00263 |
| 4    | Aggregation-induced emission: phenomenon, mechanism and applications  | Hong et al. | Chemical Communications           | 2009 | 2706            | 208.15                      | Review       | 10.1039/b904665h          |
| 5    | Aggregation-Induced Emission: The Whole Is More Brilliant than the Parts | Mei et al.  | Advanced Materials                | 2014 | 1880            | 235.00                      | Review       | 10.1002/adma.201401356    |
| 6    | Atomically Precise Colloidal Metal Nanoclusters and Nanoparticles: Fundamentals and Opportunities | Jin et al.  | Chemical Reviews                  | 2016 | 1360            | 226.67                      | Review       | 10.1021/acs.chemrev.5b00703 |
| 7    | New sensing mechanisms for design of fluorescent chemosensors emerging in recent years | Wu et al.   | Chemical Society Reviews          | 2011 | 1282            | 116.55                      | Review       | 10.1039/c0cs00224k       |
| 8    | Bioprobes Based on AIE Fluorogens                                     | Ding et al. | Accounts of Chemical Research     | 2013 | 1241            | 137.89                      | Review       | 10.1021/ar3003464         |
| 9    | Recent advances in organic mechanofluorochromic materials             | Chi et al.  | Chemical Society Reviews          | 2012 | 1241            | 124.10                      | Review       | 10.1039/c2cs35016e       |
| 10   | Supramolecular Hydrogelators and Hydrogels: From Soft Matter to Molecular Biomaterials | Du et al.   | Chemical Reviews                  | 2015 | 978             | 139.71                      | Review       | 10.1021/acs.chemrev.5b00299 |
| 11   | The Spectral Signatures of Frenkel Polarons in H- and J-Aggregates    | Spano, F.C. | Accounts of Chemical Research     | 2010 | 967             | 80.58                       | Article      | 10.1021/ar900233v         |
| 12   | Acetylenic Polymers: Syntheses, Structures, and Functions             | Liu et al.  | Chemical Reviews                  | 2009 | 944             | 72.62                       | Review       | 10.1021/cr900149d         |
| 13   | Recent advances in organic thermally activated delayed fluorescence materials | Yung et al. | Chemical Society Reviews          | 2017 | 943             | 188.60                      | Review       | 10.1039/c6cs00368k        |
| 14   | Synthesis, light emission, nanoaggregation, and restricted intramolecular rotation of 1,1-substituted 2,3,4,5-tetraphenylsiloles | Chen et al. | Chemistry of Materials             | 2003 | 930             | 48.95                       | Article      | 10.1021/cm021715z         |
| 15   | AIE macromolecules: syntheses, structures and functionalities          | Hu et al.   | Chemical Society Reviews          | 2014 | 922             | 115.25                      | Review       | 10.1039/c4cs00044g        |
| 16   | Near-infrared fluorophores for biomedical imaging                     | Hong et al. | Nature Biomedical Engineering     | 2017 | 917             | 183.40                      | Review       | 10.1038/s41551-016-0010   |
| 17   | From Aggregation-Induced Emission of Au(I)-Thiolate Complexes to Ultrabright Au(0)@Au(I)-Thiolate Core-Shell Nanoclusters | Luo et al.  | Journal of The American Chemical Society | 2012 | 907             | 90.70                       | Article      | 10.1021/ja306199p         |
| 18   | Biosensing by luminogens with aggregation-induced emission characteristics | Kwok et al. | Chemical Society Reviews          | 2015 | 810             | 115.71                      | Review       | 10.1039/c4cs00325j        |

(Continues)
Nevertheless, titles and abstracts of papers from regions outside China were equally systematized and found to be classified into two relatively separated clusters, which were presented in Figure 8B. Two separated clusters demonstrated two research priorities distinctively, which exhibited the novel design strategies of AIEgens and the mechanism of AIE phenomena. The yellow cluster in Figure 8B focused on the design of new AIEgens or fluorescent probes, including “design,” “light-emitting-diodes,” “probe,” “enhancement,” “self-assembly,” “emitters,” “electroluminescence,” and “efficient.” Meanwhile, the blue cluster illustrated the explorative mechanism of the AIE phenomena, including keywords like “fluorescence,” “photophysical properties,” “optical-properties,” “solid-state,” “charge-transfer,” “chromophores,” and “piezochromic luminescence” and so on.

It was worth mentioning that the main difference between the research scopes in and outside China was that the researchers in China paid more attention to the application of AIEgens in biology and medicine. Though our own perspectives, a growing number of multidisciplinary funding projects supported by the National Natural Science Foundation of China, especially for biomedicine, promoted more interdisciplinary studies between biomedicine and AIE filed in recent years. The prosperity in these projects indicates

| Rank | Title                                                                 | Authors          | Journal                        | Year | Total citations | Average citations per year | Article type | DOI                   |
|------|-----------------------------------------------------------------------|------------------|--------------------------------|------|-----------------|----------------------------|--------------|-----------------------|
| 19   | Optical chemosensors and reagents to detect explosives                | Salinas et al.   | Chemical Society Reviews       | 2012 | 801             | 80.10                      | Review       | 10.1039/c1cs15173h   |
| 20   | Recent progress on polymer-based fluorescent and colorimetric chemosensors | Kim et al.      | Chemical Society Reviews       | 2011 | 770             | 70.00                      | Review       | 10.1039/c0cs00058b   |
| 21   | Purely Organic Thermally Activated Delayed Fluorescence Materials for Organic Light-Emitting Diodes | Wong et al.     | Advanced Materials             | 2017 | 760             | 152.00                     | Review       | 10.1002/adma.201605444 |
| 22   | Fluorescent biochemosensors based on silole and tetraphenylethene luminogens with aggregation-induced emission feature | Wang et al.     | Journal of Materials Chemistry  | 2010 | 698             | 58.17                      | Article      | 10.1039/b921610c     |
| 23   | Polymer-encapsulated organic nanoparticles for fluorescence and photoacoustic imaging | Li et al.       | Chemical Society Reviews       | 2014 | 656             | 82.00                      | Review       | 10.1039/c4cs00014e   |
| 24   | Changing the Behavior of Chromophores from Aggregation-Caused Quenching to Aggregation-Induced Emission: Development of Highly Efficient Light Emitters in the Solid State | Yuan et al.     | Advanced Materials             | 2010 | 652             | 54.33                      | Communication | 10.1002/adma.200904056 |
| 25   | Supramolecular Amphiphiles Based on Host-Guest Molecular Recognition Motifs | Yu et al.       | Chemical Reviews               | 2015 | 634             | 90.57                      | Review       | 10.1021/cr5005315    |
| 26   | Fluorescence-based explosive detection: from mechanisms to sensory materials | Sun et al.      | Chemical Society Reviews       | 2015 | 616             | 88.00                      | Review       | 10.1039/c5cs00496a   |
| 27   | Twisted Intramolecular Charge Transfer and Aggregation-Induced Emission of BODIPY Derivatives | Hu et al.       | Journal of Physical Chemistry C | 2009 | 612             | 47.08                      | Article      | 10.1021/jp902962h    |
| 28   | Photochromic Materials: More Than Meets The Eye                       | Zhang et al.    | Advanced Materials             | 2013 | 590             | 65.56                      | Review       | 10.1002/adma.201201521 |
| 29   | Tetraphenylethene: a versatile AIE building block for the construction of efficient luminescent materials for organic light-emitting diodes | Zhao et al.     | Journal of Materials Chemistry  | 2012 | 561             | 56.10                      | Review       | 10.1039/c2jm31949g   |
| 30   | A Photostable AIE Luminogen for Specific Mitochondrial Imaging and Tracking | Leung et al.    | Journal of The American Chemical Society | 2013 | 552             | 61.33                      | Communication | 10.1021/ja310324q    |
that the researchers in different disciplines directed their gaze at the light-emitting properties and applications of AIEgens. Thus far, AIEgens have been applied to bacterial imaging and identification,[24] cellular organelle imaging (lysosome,[5,25] cell membrane,[6] mitochondria,[26] lipid droplets,[27] nucleus,[28]) photoacoustic imaging,[29] and photothermal therapy.[30] Those applications unleashed the great clinical transformation potential of AIEgens.

3.7 AIE hotspot foamtree analysis on NIR-II

In order to decipher the frontier hotspot of AIE field more adequately, Carrot², a website-based analyzing tool, was conducted to visualize the latest 500 papers on AIE from Pubmed. The titles, abstracts, and keywords of these papers were clustered to create a hotspot foamtree (Figure 9A). The areas of clusters were based on the number of papers in certain fields, and the brief title in a cluster stood for the high-frequency word. The results demonstrated that AIEgens used for “biological imaging,” “photodynamic therapy,” “fluorescent sensing,” “bacteria detecting” and “NIR-II fluorescence imaging” would be research hotspots for a period of time in the future. Among all the presented clusters, the cluster of “NIR-II Emission” closely related to our research scope and therefore attracted our interest most. We further placed our emphasis on a total of 20 pieces of AIE research related to the NIR-II window (Figure 9B; Table 6). Owing to the advantages that the imaging in NIR-II biological window have the superiorities of large penetration depth, low autofluorescence, reduced tissue scattering, and high signal-to-background ratio,[31] it has received tremendous attention. As an authorship-co-occurrence network visualized in Figure 9C by these 20 papers shown, authors were closely related to “Tang Ben Zhong” and divided into two detached groups at a threshold of two documents. The authors of the red cluster on the left published articles on designing instructions of excretable and bright AIEgens[32] and NIR-II fluorescence imaging-guided surgery for inflammatory bowel disease.[33] In the meantime, the authors of the green cluster on the right focused on multiscale intravital vascular fluorescence

![Keywords co-occurrence network analysis was applied to predict the research trends in aggregation-induced emission (AIE) field. (A) Keyword co-occurrence network of AIE researches from China. (B) Keyword co-occurrence network of AIE researches from other countries.](image-url)
3.8 Perspectives of AIE research frontiers

To properly showcase the current research hotspots, we extracted the documents of 2020 and assessed solely by conducting Citespace clustering analysis. Meticulous analysis of recently published papers allowed us to precisely predict the research trends in AIE and, in consequence, we attempted to offer an insight into the frontiers of this research area. The entire amount of AIE documents were classified into several knowledge units, and the label of each unit objectively reflected the main content (Figure 10). Smaller serial numbers of labels represented larger numbers of included documents. The top 10 clustering topics were “dye-loaded polymeric nanoparticles,” “photodynamic therapy,” “mechanofluorochromism,” “thermally activated delayed fluorescence,” “room temperature phosphorescence,” “supramolecular polymer,” “clustering-triggered emission,” “biomedical applications,” “circularly polarized luminescence,” “photochemistry.” We looked over some relevant AIE literature and found these topics were fairly representative. For instance, purely organic materials with room temperature phosphorescent (RTP) characteristics were becoming increasingly popular. Wu et al. reported the first persistent RTP with lifetime up to 0.5 s from simple triarylboranes which had no lone pairs. Yosuke et al. found the first mechanoresponsive turn-on of purely organic RTP, which was associated with the amorphization of crystals. Additionally, on the topic of thermally activated delayed fluorescence (TADF), Li et al. modified the indole-based D-A-D molecule by a bilateral amide end group linked with long alpha-lipoic alkyl chains, which was a TADF emitter with high emission efficiency both in the monomeric and aggregated state. To a certain extent, this figure predicted that the abovementioned topics, such as RTP AIEgens, photodynamic therapy and AIEgen-loaded polymeric nanoprobes, might draw more and more attentions in the foreseeable future.

4 SUMMARY

In summary, AIE is a photophysical phenomenon displayed by a group of optical materials that are highly luminescent in aggregates but nonemissive when dissolved in good solvents. On the occasion of this concept being proposed for 20 years, our study presents a bibliometric analysis of scientific literature on AIE scope and offers a historical review in a specific dimension. This field has undergone an expeditious and steep growth in the last two decades. We identify the research trend according to publications and citations over the years, productive countries/regions and authors, leading journals and institutions, influential papers, recurrent keywords, and relevant NIR-II hotspots, together with prophetic research frontiers. In this field, as noted in results, Chinese institutions play a leading role with institutions from other countries increasingly involved. The global cooperation tends to be closer and more prosperous in recent years. Furthermore, Tang Ben Zhong and his research team are in a leadership position, and Hong Kong University of Science and Technology is the most copious institution. Subsequently, researchers with high citations, keyword co-occurrence network, NIR-II related foamtree, and frontier perspective on AIE are vividly visualized via different kinds of software. In the AIE research
| No. | Title                                                                 | Authors          | Journal                      | Year | Article type | DOI               |
|-----|----------------------------------------------------------------------|------------------|------------------------------|------|--------------|------------------|
| 1   | Enzyme-activatable fluorescent probes for β-galactosidase: from design to biological applications. | Yao et al.       | Chemical Science             | 2021 | Review       | 10.1039/d1sc02069b |
| 2   | Aggregation-Induced Emission (AIE) Nanoparticles-Assisted NIR-II Fluorescence Imaging-Guided Diagnosis and Surgery for Inflammatory Bowel Disease (IBD). | Fan et al.       | Advanced Healthcare Materials | 2021 | Article      | 10.1002/adhm.202101043 |
| 3   | Structural and process controls of AIEgens for NIR-II theranostics.   | Liu et al.       | Chemical Science             | 2021 | Review       | 10.1039/d0sc02911d |
| 4   | An Activatable Probe with Aggregation-Induced Emission for Detecting and Imaging Herbal Medicine Induced Liver Injury with Optoacoustic Imaging and NIR-II Fluorescence Imaging. | Sun et al.       | Advanced Healthcare Materials | 2021 | Article      | 10.1002/adhm.202100867 |
| 5   | Tuning molecular aggregation to achieve highly bright AIE dots for NIR-II fluorescence imaging and NIR-I photoacoustic imaging. | Xu et al.        | Chemical Science             | 2021 | Article      | 10.1039/d0sc03160g |
| 6   | Synthesis and characterisation of N-gene targeted NIR-II fluorescent probe for selective localisation of SARS-CoV-2. | Moitra et al.    | Chemical Communications      | 2021 | Article      | 10.1039/d1cc01410b |
| 7   | A two-in-one Janus NIR-II AIEgen with balanced absorption and emission for image-guided precision surgery. | Liu et al.       | Materials Today Bio          | 2021 | Article      | 10.1016/j.mtbio.2020.100087 |
| 8   | J-aggregates of meso-[2.2] paracyclophanyl-BODIPY dye for NIR-II imaging. | Li et al.        | Nature Communications        | 2021 | Article      | 10.1038/s41467-021-22686-2 |
| 9   | Encapsulation of NIR-II AIEgens in Virus-like Particles for Bioimaging. | Min et al.       | ACS Applied Materials & Interfaces | 2021 | Article      | 10.1021/acsami.1c02691 |
| 10  | Biologically Excretable Aggregation-Induced Emission Dots for Visualizing Through the Marmosets Intravitally: Horizons in Future Clinical Nanomedicine. | Feng et al.      | Advanced Materials           | 2021 | Article      | 10.1002/adma.202008123 |
| 11  | A computational and experimental investigation of donor-acceptor BODIPY based near-infrared fluorophore for in vivo imaging. | Zhang et al.     | Bioorganic Chemistry         | 2021 | Article      | 10.1016/j.bioorg.2021.104789 |
| 12  | Ultrabright NIR-II Emissive Polymer Dots for Metastatic Ovarian Cancer Detection. | Zhou et al.      | Advanced Science             | 2021 | Article      | 10.1002/advs.202000441 |
| 13  | Aggregation-induced emission fluorophores based on strong electron-acceptor 2,2’-(anthracene-9,10-diyldiene) dimalononitrile for biological imaging in the NIR-II window. | Yang et al.      | Chemical Communications      | 2021 | Article      | 10.1039/d1cc00742d |
| 14  | In Vivo Three-Photon Imaging of Lipids using Ultrabright Fluorogens with Aggregation-Induced Emission. | Wang et al.      | Advanced Materials           | 2021 | Article      | 10.1002/adma.202007490 |
| 15  | AIE-active two-photon fluorescent nanoprobe with NIR-II light excitability for highly efficient deep brain vasculature imaging. | Samanta et al.   | Theranostics                 | 2021 | Article      | 10.7150/thno.53780 |
| 16  | Organic fluorescent nanoparticles with NIR-II emission for bioimaging and therapy. | Dang et al.      | Biomedical Materials         | 2021 | Review       | 10.1088/1748-605X/abca4a |
| 17  | Centimeter-Deep NIR-II Fluorescence Imaging with Nontoxic AIE Probes in Nonhuman Primates. | Sheng et al.     | Research                     | 2020 | Article      | 10.34133/2020/4074593 |
| 18  | Quaternary Ammonium Salt Based NIR-II Probes for in vivo Imaging. | Qu et al.        | Advanced Optical Materials   | 2019 | Article      | 10.1002/adom.201900229 |
| 19  | Self-assembled AIEgen nanoparticles for multiscale NIR-II vascular imaging. | Li et al.        | Biomaterials                 | 2021 | Article      | 10.1016/j.biomaterials.2020.12036 |
| 20  | Bright and Stable NIR-II J-Aggregated AIE Dibodipy-Based Fluorescent Probe for Dynamic In Vivo Bioimaging. | Zhang et al.     | Angewandte Chemie-International Edition | 2021 | Article      | 10.1002/anie.202012427 |
field, a multi-interdisciplinary system has been formed with aggregate science as the core subject. Recent studies pay more attention to RTP AIEgens, photodynamic therapy AIEgens and AIEgen-loaded polymeric nanoprobes. Of note, different from the comprehensive review, our study is based on bibliometric analysis and provides a unique perspective for the development of AIE field. Also, because of the analysis method, the main limitation of our study is that it could not offer specific guidance in a certain aspect of AIE field. Though significant progress has been made in the AIE area, we eagerly look forward to innovative developments in this exhilarating area of research by standing on the shoulders of giants.

ACKNOWLEDGMENTS
This work was supported by National Key Research and Development Project (2017YFC0110802), Zhejiang province Key Research and Development Project (2020C01059), National Natural Science Foundation of China (81874059, 61975172 and 61735016), Zhejiang Engineering Research Center of Cognitive Healthcare (2017E10011), National Key Scientific Instrument and Equipment Development Project (81827804), and Fundamental Research Funds for the Central Universities (2020-KYY-511108-0007).

CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
Qiming Xia and Yiyin Zhang contributed equally to this work. Qiming Xia, Yiyin Zhang, and Xiaoxiao Fan conceived the project and wrote the manuscript. Yirun Li, Yixuan Li, and Yiling Li collected and collated the data from Web of Science Core Collection. Qiming Xia, Yiyin Zhang, and Xiaoxiao Fan supervised research and acquired financial support. All authors discussed the results and comments on the manuscript.

ORCID
Zhe Feng https://orcid.org/0000-0001-6763-9616
Hui Lin https://orcid.org/0000-0001-5459-800X

REFERENCES
1. J. Mei, N. L. Leung, R. T. Kwok, J. W. Lam, B. Z. Tang, Chem. Rev. 2015, 115, 11718.
2. J. D. Luo, Z. L. Xie, J. W. Y. Lam, L. Cheng, H. Y. Chen, C. F. Qu, H. S. Kwok, X. W. Zhan, Y. Q. Liu, D. B. Zhu, B. Z. Tang, Chem. Commun. 2001, 21 1740.
3. Y. Huang, J. Xing, Q. Gong, L. C. Chen, G. Liu, C. Yao, Z. Wang, H. L. Zhang, Z. Chen, Q. Zhang, Nat. Commun. 2019, 10, 169.
4. Y. Hong, J. W. Lam, B. Z. Tang, Chem. Commun. 2009, 4332.
5. a) R. R. Hu, C. F. A. Gomez-Duran, J. W. Y. Lam, J. L. Belmonte-Vazquez, C. M. Deng, S. J. Chen, R. Q. Ye, E. Pena-Cabrera, Y. C. Zhong, K. S. Wong, B. Z. Tang, Chem. Commun. 2012, 48, 10099. b) C. W. T. Leung, Z. M. Wang, E. G. Zhao, Y. N. Hong, S. J. Chen, R. T. K. Kwok, A. C. S. Leung, R. S. Wen, B. S. Li, J. W. Y. Lam, B. Z. Tang, Adv. Healthcare Mat. 2016, 5, 427.
6. Y. H. Li, Y. Q. Wu, J. Chang, M. Chen, R. Liu, F. Y. Li, Chem. Commun. 2013, 49, 11335.
7. a) Y. Li, L. Xu, B. Su, Chem. Commun. Cambridge. England. 2012, 48, 4109. b) N. Zhao, J. W. Lam, H. H. Sung, H. M. Su, I. D. Williams, K. S. Wong, B. Z. Tang, Chemistry 2014, 20, 133. c) Y. Guo, X. Feng, T. Han, S. Wang, Z. Lin, Y. Dong, B. Wang, J. Am. Chem. Soc. 2014, 136, 15485.
8. J. Mei, J. Hong, J. W. Lam, A. Qin, Y. Tang, B. Z. Tang, Adv. Mater. 2014, 26, 5429.
9. J. Liu, H. Su, L. Meng, Y. Zhao, C. Deng, J. C. Y. Ng, P. Lu, M. Faisal, J. W. Y. Lam, X. Huang, H. Wu, K. S. Wong, B. Z. Tang, Chem. Sci. 2012, 3, 2737.
10. N. Zhao, M. Li, Y. Yan, J. W. Y. Lam, Y. L. Zhang, Y. S. Zhao, K. S. Wong, B. Z. Tang, Mater. Chem. C 2013, 1, 4640.
11. D. Zhao, F. Fan, J. Cheng, Y. Zhang, K. S. Wong, V. G. Chigrinov, H. S. Kwok, L. Guo, B. Z. Tang, Adv. Opt. Mat. 2015, 3, 199.
12. a) R. Dalpe, Scientometrics 2002, 55, 189. b) A. Pritchard, J. Docum. Technol. 1969, 25, 348.
13. W. Marx, L. Bornmann, A. Barth, L. Leydesdorff, J.Assoc. Inform. Sci. Technol. 2014, 65, 751.
14. a) Q.-H. Pu, Q.-J. Lu, H.-Y. Su, Bmj Open 2016, 6. b) D. Xing, Y. Zhao, S. Dong, J. Lin, Int. J. Rheumat. Dis. 2018, 21, 1372.
15. X. Lim, Nature, 2016, 531, 26.
16. T. Cheisson, E. J. Schelter, Science 2019, 363, 489.
17. a) M. Zhang, X. Zhai, M. Sun, T. Ma, Y. Huang, B. Huang, Y. Du, C. Yan, Chem. Soc. Rev. 2020, 49, 9220. b) K. Binnemans, Chem. Rev. 2009, 109, 4283; c) S. V. Eliseeva, J.-C. G. Buenzli, Chem. Soc. Rev. 2010, 39, 189.
18. a) Y. Hong, J. W. Y. Lam, B. Z. Tang, Chem. Commun. 2009, 4332. b) S. Zhang, A. Qin, J. Sun, B. Tang, Prog. Chem. 2011, 23, 623.
19. M. Wang, G. Zhang, D. Zhang, D. Zhu, B. Z. Tang, J. Mat. Chem. 2010, 20, 1858.
20. Z. Chi, X. Zhang, B. Xu, X. Zhou, C. Ma, Y. Zhang, S. Liu, J. Xu, Chem. Soc. Rev. 2012, 41, 3878.
21. H. Small, J. Am. Soc. Inform. Sci. 1973, 24, 265.
Qiming Xia received his bachelor’s degree in clinical medicine in 2020 from Zhejiang University. He is now pursuing an interdisciplinary PhD in general surgery and optics under the supervision of Prof. Hui Lin and Prof. Jun Qian in the School of Medicine, Zhejiang University. His current research interests include AIE nanoparticle assisted NIR-II imaging-guided surgery and basic medical research of liver cancer.

Yiyin Zhang received her master degree in oncology in 2020 from Fudan University. She continued to pursue her PhD in general surgery in School of Medicine, Zhejiang University, under the supervision of Prof. Hui Lin and Prof. Jun Qian. Since 2020, she started an interdisciplinary study of general surgery and optics, aiming to expand the application of biomedical optics in clinical medicine. Her current research interests include the NIR-II fluorescence imaging and basic research of tumor microenvironment.

Xiaoxiao Fan received his MD in general surgery in School of Medicine, Zhejiang University. He worked as a surgeon in the Department of General Surgery, Sir Run Run Shaw Hospital, School of Medicine, Zhejiang University from 2014 to 2017. He now works as a postdoctoral research fellow in biophotonics under the supervision of Prof. Jun Qian in the College of Optical Science and Engineering, Zhejiang University. His current research interests involve NIR-II fluorescence imaging-guided treatment and biomedical optics.

Dr. Jun Qian received his PhD degree from the Department of Optical Engineering of Zhejiang University in 2009. He is now a professor in the College of Optical Science and Engineering, Zhejiang University. Dr. Qian’s research work focuses on Biomedical-Photonics, especially deep-tissue and fluorescence bioimaging.

Prof. Hui Lin received his PhD in general surgery in School of Medicine, Zhejiang University. He then works as a surgeon in the Department of General Surgery, Sir Run Run Shaw Hospital, School of Medicine, Zhejiang University. Since 2020, he has been appointed as the vice director of the College of Biomedical Engineering and Instrument Science, Zhejiang University. His research interests include the mechanism and NIR-II imaging-guided treatment of liver cancer.

How to cite this article: Q. Xia, Y. Zhang, Y. Li, Y. Li, Z. Feng, X. Fan, J. Qian, H. Lin, Aggregate 2022, 3, e152. https://doi.org/10.1002/agt2.152