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Research trends and impact report on Aggregation-Induced Emission (AIE), 2001–2021

Analytical Services

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Introduction

Discoveries and applications of new knowledge have propelled the advancement of human civilization. However, new knowledge is inseparable from new concepts. Challenging previous ideas and setting out new ones not only change people's way of thinking but also drive the development of science. For example, Albert Einstein's quantum theory of light successfully explained experimental photoelectric effects in the early 20th century and prompted the development of quantum theory. Einstein's findings transformed the world and brought the science of light to the forefront, playing an essential role in the development of civilization. Hermann Staudinger's pioneering theories on polymer structures challenged the leading colloidal theory of his time and became the basis for development in modern chemistry and material sciences. Research on synthetic metals, also known as conductive polymers, by Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, invalidated the idea that all polymers are insulators, and led to the conception of organic optoelectronics.

For the past 2,000 years, humans have sought to understand the concept of light, and in the course of developing various theories and technologies, have achieved many milestones in optical science. As early as 1666, Isaac Newton had studied the color and dispersion of light. In 1678, Christiaan Huygens proposed the wave theory of light. James Clerk Maxwell proposed the electromagnetic theory of light in 1860, and in 1879, Thomas Alva Edison invented the light bulb, which changed the face of human society and improved people's standard of living. In 1887, Heinrich Rudolf Hertz discovered the photoelectric effect, which made light-electrical conversion possible. In 1996, Charles Kuen Kao invented fiber optics, which revolutionized telecommunications, transformed the world, and advanced social progress. Given the importance of research on the subject of light, the United Nations named 2015 the "International Year of Light" to promote and publicize light-related scientific achievements and their role in addressing challenges related to health, water, energy, the environment, food, education, security, and poverty.

The interactions between light and matter are mainly through the absorption and emission of light. People had already begun to study light emissions in the mid-19th century. In 1852, while studying the fluorescence of quinine and chlorophyll, George Gabriel Stokes found that, under the irradiation of short wavelength light, some substances can emit light with a wavelength longer than that of the excited light. In studies of luminescent materials in the 1950s, Theodor Förster and others discovered that pyrene's fluorescence intensity is closely associated with its concentration: this type of small organic molecules emit strong luminescence in diluted solutions but show weak or eliminated emission in high-concentration solutions. This phenomenon is called aggregation-caused quenching (ACQ). Luminescent materials are usually applied in a solid or aggregated state, which require high luminescence efficiency under those circumstances. However, the ACQ effect in materials dramatically reduces the luminescence efficiency under aggregated states, limiting the performance of devices.

To mitigate the ACQ effect on materials' luminescence efficiency, researchers have adopted a series of chemical, physical, and engineering methods and approaches to inhibit the aggregation of molecules. These efforts include linking chains, macrocyclic groups, and dendritic- or wedge-shaped functional groups to aromatic rings in covalent chemical bonds to prevent the aggregation of molecules. Other methods, such as coating luminescent compounds with surfactants or mixing them in a transparent polymer medium, were also adopted. However, chemical approaches often involve tedious synthesis processes. Attaching bulky structural groups to aromatic groups can also distort the conformation and conjugation of the luminescent material, affecting the emission wavelength and efficiency. Meanwhile, physical methods require precision and lack reproducibility. The capping agents and polymers used in these methods generally do not emit light. The use of these materials can dilute the luminescent units in the system and hinder charge transport. Thus, attempts that interfered with the aggregation of luminescent materials only achieved limited success. In many cases, suppressing the aggregation also brought forth new problems. Human interference to inhibit aggregation cannot address the root cause of ACQ effects in luminescent molecules, as aggregation is a spontaneous internal process. Therefore, the ideal solution is to take full advantage of the molecules' aggregating characteristics to improve luminescence intensity under the aggregated or solid state.

In 2001, Ben Zhong Tang, an Academician of the Chinese Academy of Science, found that 1-methyl-1,2,3,4,5-pentaphenylsilile does not emit light in acetonitrile. However, it emits strong green fluorescence in an acetonitrile solution containing large amounts of poor solvent (water). This phenomenon led Tang to propose the concept of aggregation-induced emission (AIE)[1] for the very first time. Through subsequent research and experiments, he theorized and verified the mechanism behind AIE, called the restriction of intramolecular motion (RIM). Tang's work pioneered a new field of research that is led by Chinese scientists. Based on the RIM mechanism, researchers designed and constructed a large number of structurally diverse small molecules, polymers, and organometallic complexes with AIE characteristics. Today, the RIM mechanism has been widely adopted by the scientific community to explain the phenomenon of molecular aggregation-induced luminescence. As a new class of luminescent material, AIE materials have been broadly applied in various fields and interdisciplinary areas such as optoelectronic devices, chemical sensing, and biological diagnosis and imaging. Compared to traditional ACQ luminescent materials, AIE materials have shown unique advantages.

Originating from China, AIE research not only challenged the scientific consensus about aggregation-caused luminescence quenching, but also transformed previous notions about

[1] Luo, J., Xie, Z., Lam, J., Cheng, L., Tang, B. Z., & Chen, H., et al. (2001). "Aggregation-Induced Emission of 1-Methyl-1,2,3,4,5-Pentaphenylsilole." Chemical Communications, (18), 1740-1741. doi:10.1039/b105159h.

aggregation-state luminescent technologies. It provided new avenues for designing high-efficiency solid-state luminescent materials. Moreover, AIE research has broadened and deepened the understanding and research on molecular luminescence mechanisms, providing a holistic view of the field, changing previously held ideas, and forming a new field of scientific study. Consequently, AIE research has received attention from researchers in the fields of chemistry, materials science, biology, and medicine. For example, as the only type of material system proposed and developed by the Chinese, AIE luminescent dots were listed as an essential type of material to support the upcoming nano-light era by the journal *Nature* (2016). AIE materials show great potential in medical applications, including diagnosis and imaging, which may revolutionize imaging technology in the biomedical field (*Nature* special issue 2020). AIE technology was also named one of the top 10 emerging technologies in the field of chemistry in 2020 by the International Union of Pure and Applied Chemistry (IUPAC), one of the most renowned organizations in chemistry.

Since the concept of AIE was first proposed in 2001, it has gradually grown from an idea that originated in China to a field of science that attracts dedicated researchers from around the world. Elsevier's data analytics team used AIE experts' interpretation of current theoretical, technological, and industrial development trends in the field for reference to collect AIE-related global scientific publications (from the Scopus[2] database) to serve as a publication set in the field of AIE[3]. This was undertaken to present, accurately and objectively, the development of AIE research over the past two decades and the latest scientific advancements in the field; to facilitate the establishment of a systematic and theoretical knowledge base; and to help build a Chinese-led international collaboration platform to promote innovation, industrial transformation, and applications of AIE and its related fields.

The AIE-related publications were collected and classified from the full Scopus database using a keyword sequence[4]. To precisely define the scope, Elsevier's research analytics team considered more than 300 keywords provided by field experts as initial input data and performed split retrieval, cross retrieval, and reverse retrieval on all keywords in the entire database. The Elsevier team analyzed the precision and recall results for each query segment, some of which were accompanied by experts' manual identification to allow a controllable expansion and restriction on the sequence. The keyword sequence located each article by the article's title, abstract, and keywords (including indexed keywords and author keywords). The sequence can also be updated on a rolling basis, annually, to continuously include new publications; this helps in facilitating the process of tracking the latest research developments.

As an emerging research field closely related to the high-tech industries, AIE research is undergoing translation of scientific results from the lab into applicable technologies and products. To accurately

[2] Scopus is Elsevier's database of peer-reviewed article abstracts and citations, covering 77.3 million articles published in more than 39,000 journals, serials, and conference proceedings from 5,000 publishers in approximately 105 countries. The coverage of Scopus is multilingual and global: approximately 46% of publications in Scopus are in languages other than English (or in English and other languages). In addition, more than half of Scopus content comes from outside North America, representing many countries in Europe, Latin America, Africa, and the Asia-Pacific region.

[3] Articles that were not in the Scopus database have not been included in this report.

[4] See Appendix I for details on the final keyword sequence.

and effectively reflect the industrial transformation and application value of AIE research and the current technology status of the field, Elsevier's data analytics team also searched and collected related patents. The team conducted a comprehensive search for AIE patents using keywords and cooperative patent classification (CPC) in patent documents issued by patent offices in 115 countries and regions worldwide. These documents were collected by LexisNexis® PatentSight®[5], a patent database of LexisNexis, which is a subsidiary of RELX.

Data from the collection of scientific publications and patents show that the number of relevant publications in the field of AIE has increased exponentially since 2001, with more than 1,100 publications in the first half of 2022 alone. As of 2021, more than 24,000 researchers, 2,200 research institutions, and 76 countries of more than 190 countries worldwide participated in AIE-related research, yielding more than 1,600 patents in the field. These figures show that AIE has become a hotspot of global research.

This report combines publications and patent data with an analysis of national and international research progress, offering a systematic overview of the AIE field. The report is divided into four chapters. Chapter 1 presents an overview of research performance in the field of AIE, describes the overall publication output and trends in scientific development over the past two decades, and showcases the rapid growth and internationalization of AIE research. Chapter 2 constitutes a performance overview of research collaboration in AIE research that introduces different approaches to collaboration and provides suggestions for the future. Chapter 3 lays out areas of research in the field of AIE, with a view into research subjects across disciplines, extended research areas, and popular topics, to demonstrate the facets of the field and to illustrate that AIE research is moving out of its initial phase into an innovation-intensive period. Lastly, Chapter 4 explores the translation of basic research in AIE into industrial applications, showcasing the transformation of theoretical research findings to applications through academic–corporate collaboration, the knowledge flow from articles to patents, and relevant analyses of the patents.

Through data analysis and corresponding visualizations, this report presents an objective overview of global and regional scholarly output, research trends, and conversion of basic AIE research into applications over the past two decades. The report aims to provide a guide for the strategic planning of scientific advancement, to facilitate the development of innovative technology, to support talent training, and to prompt changes in policy related to the field. Moreover, by showcasing the research hotspots within the field, this report tries to provide basic information for researchers to refer to and use as appropriate. As with any scientific publication, the report comes with its limitations, and we welcome comments and suggestions.

[5] LexisNexis® PatentSight® has a global patent valuation tool, Patent Asset Index™. This tool, developed through systematic science and offered exclusively by LexisNexis® PatentSight®, identifies high-value patents from a large number of patents as a prerequisite for reliable patent analysis. In addition, the tool can analyze patent portfolios against competitors, suppliers, customers, specified technology areas, and new market entrants to identify potential opportunities and threats. For more information, please visit: https://cn.lexisnexisip.com/products/patent-sight/

Chapter 1

Overview of AIE research performance

Key Data

8,843

Total volume of publications in the AIE field (2001–2021)

1.9

Normalized citation impact (Field weighted citation impact, FWCI[6]) (2001–2021)

44.9%

Compound annual growth rate (CAGR) of the scholarly outputs (2001–2021)

304,862

Total citations of articles in the AIE field (2001–2021)

23,900

Number of authors who published articles in the AIE field (2001–2021)

Hong Kong University of Science and Technology

Top contributor in the AIE field (2001–2021)

410

Number of top 1% highly cited articles from 2001 to 2021, accounting for 4.6% of all publications in the AIE field

2,883

Number of top 10% highly cited articles from 2001 to 2021, accounting for 32.6% of all publications in the AIE field

3,854

Number of corresponding authors in the AIE Field (2001–2021)

19,897

Number of active authors in the AIE field (2001–2021[7])

[6] See Chapter I, Section I of the main text for details on the elaboration of the FWCI indicators, and Appendix V for details on the calculation.

[7] See Chapter 1, Section 2 of the main text for a detailed definition of active authorship.

Overall performance of AIE research

Scholarly output, also known as the volume of scientific publication, is defined as the total number of articles in a given research field within a fixed time period. These outputs include journal articles, conference proceedings, review articles, and book series. These publications represent, to some extent, the productivity of researchers in a specific field. In addition to assessing the output of the field, evaluating the scholarly impact of the publications provides another perspective on scientific advancements in the field.

This section will analyze the global scholarly output and scholarly impact within the field of Aggregation Induced Emission (AIE) from 2001 to 2021, with special attention to the overall performance and trends in major countries and regions worldwide through the number of publications and their scholarly impact.

Analysis of the overall performance of scientific research in AIE shows that:

The amount of global research within the AIE field has been growing annually since 2001 and has experienced an exponential surge in the past decade (2012–2021). Of the total published articles in the field, 95.8% had been published in the last decade.

The scientific impact of articles related to the AIE field is high, with a Field Weighted Citation Impact (FWCI) of 1.9 from 2001 to 2021. This value is nearly twice the global average for scholarly impact across all disciplines.

Globally, AIE-related publications are concentrated in China. With the rapid development of China's economy and the nation's continuous investment in basic research, China has published 6,602 AIE-related articles over the past two decades, accounting for 74.7% of the total number. As AIE research continues to grow, the number of countries and regions entering the field is progressively increasing. As of 2021, 76 countries and regions have published AIE-related research, indicating the internationalization of the field.

I. Overall scholarly output

i. Global research performance in AIE

From 2001 to 2021, AIE-related research publications continued to grow rapidly. As shown in Figure 1.1.1.1, the number of publications in the field has increased over the past two decades, from 1 in 2001 to 1,673 in 2021, with a total of 8,843 publications and a compound annual growth rate (CAGR[8]) of 44.9% over the 21-year period.

Research publication output by year in the global AIE field grew faster in the more recent decade (2012–2021) than in the earlier decade (2012–2021); from 1 publication in 2001 to 128 publications in 2011, an increase of 127 publications in 11 years has been noted. In 2021, the number of publications reached 1,673, a 1,482-increase compared to the 191 publications in 2012. Further, the total number of AIE-related publications in the past decade was 8,470, which accounts for 95.8% of all publications in the field of AIE worldwide, indicating that scholarly output in the field was concentrated in the last decade. AIE continues to be an emerging and fast-growing field.

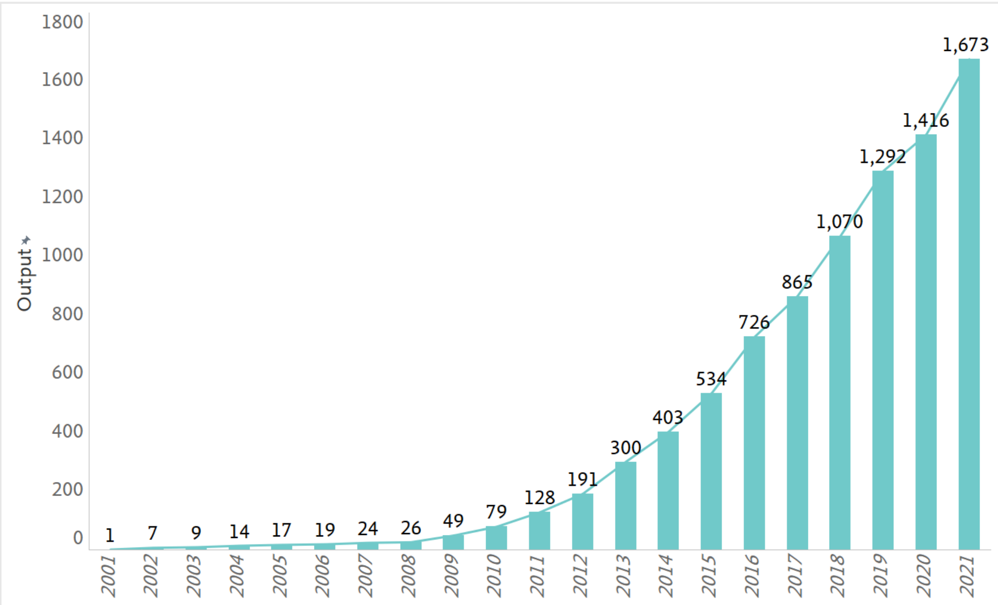

Figure 1.1.1.1 Global scholarly output in the field of AIE, 2001–2021

ii. Comparing the performance of scholarly output in countries and regions

With the continuous development of AIE research, the number of countries involved in the field of AIE is also increasing. Over the past two decades, a total of 76 countries/regions have published 8,843 AIE-related articles, indicative of increased attention directed to the field. Initiated and led by Chinese researchers, the field of AIE research continues to grow internationally.

[8] See Appendix V for details on the calculation of the compound annual growth rate.

Figure 1.1.1.2 shows the yearly trend in AIE publications for the benchmarked countries[9]. China led the list as the country with the highest number of publications. From 2001 to 2021, the number of AIE-related publications in China increased from 11 in 2001 to 1,272 in 2021, resulting in a CAGR of 43.0%, which is higher than in the other benchmarked countries and is close to the global average (44.9%). Over the past two decades, China has published 6,602 AIE-related publications, accounting for 74.7% of global AIE articles. Arguably, China is not only the originator of the AIE research field, but also the main driver of AIE research in the Asia-Pacific region and, perhaps, the world.

Overall, the benchmarked countries have shown an increase in the number of AIE publications. India has the second-highest total scholarly output in the field, with 768 publications during the period 2001–2021. This is followed by Japan, the United States, and Singapore, with 430, 429, and 351 publications, respectively.

In 2012, most countries in this analysis started witnessing a significant increase in the number of publications, including some with rapid growth; in recent years, India has had the fastest increase in publications, with 153 AIE articles published in 2021, an increase of 141 compared to 2012. Japan stepped into AIE research relatively early and its output has shown significant growth since 2008, ranking it third in terms of total publications for years. The United States has had notable growth in AIE research in the last decade and, in 2021, it outpaced Japan as the country with the third-highest number of AIE publications. South Korea, surpassing Singapore in 2021, became the fifth largest contributor by output in the AIE field.

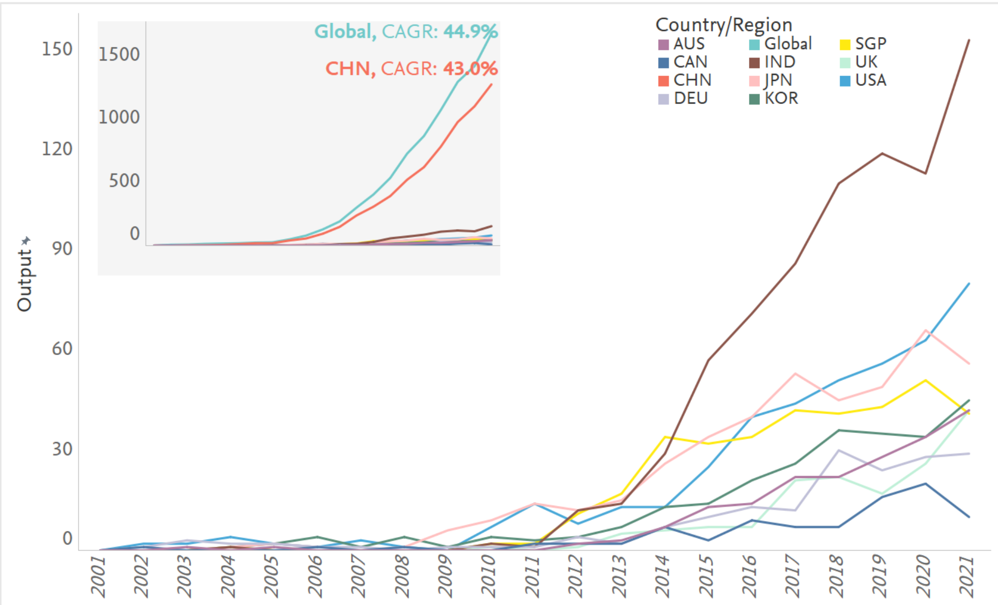

Figure 1.1.1.2 Yearly trend of publications in the field of AIE for the benchmarked countries and the world, 2001–2021 (Country code: AUS-Australia, CAN-Canada, CHN-China, DEU-Germany, IND-India, JPN-Japan, KOR-Korea, SGP-Singapore, UK-UK, USA-US. Global-Global. CAGR indicates compound annual growth rate, see Appendix V for details)

[9] The countries selected for comparison in this report include Australia, Canada, China, Germany, India, Japan, South Korea, Singapore, the United Kingdom, and the United States.

Among global regions, as shown in Figure 1.1.1.3, the Asia-Pacific region[10] (excluding the Chinese mainland) published a total of 3,268 AIE articles during the period 2001–2021, accounting for 37.0% of global publications, and it is also the region with the fastest growth rate. Europe and North America[11] have published relatively fewer articles in this field, each producing 824 and 510 AIE-related publications over the past two decades, with a CAGR of 26.6% and 19.6%, respectively. The lower volume and the growth rate of AIE publications in global regions, as compared to China, again indicate that the AIE research field is led by Chinese researchers.

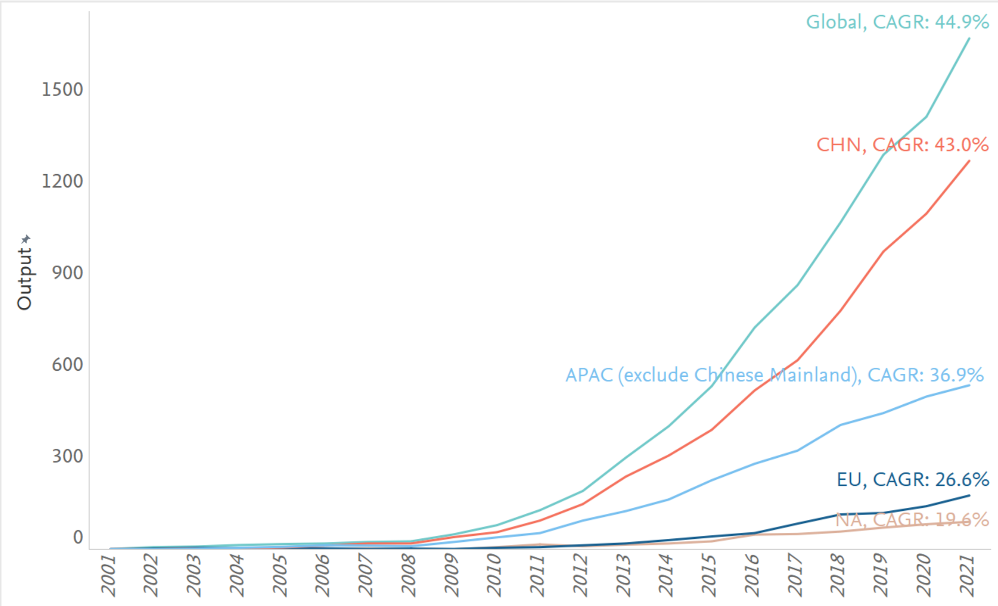

Figure 1.1.1.3 Comparisons of the yearly trend in AIE publications for the world, China, and different global regions[12], 2001–2021 (Global region code: APAC-Asia Pacific (excluding the Chinese mainland), EU-Europe, NA-North America. CAGR indicates compound annual growth rate, see Appendix V for details)

As shown in Figure 1.1.1.4, scholarly output in the field of AIE in China's national region has also grown rapidly in recent years. From 2001 to 2021, the Yangtze River Delta (YRD) region published 1,936 AIE-related articles, the highest output in China, followed by the Beijing-Tianjin-Hebei (BTH) and Pearl River Delta (PRD) regions, with a total of 1,766 and 1,601 publications, respectively. Both numbers exceeded the total output of publications in Europe and North America combined. The YRD, PRD, and BTH regions have shown similar growth trends. The publication growth rate in the YRD region has rapidly increased since 2013 and surpassed the BTH region as the region with the most publications in 2018. Hong Kong, China, had a growth rate similar to the other three regions in the Chinese mainland from 2001 to 2014, but after 2014, the growth rate began to slow down. Taiwan, China had the least number of publications, with 237 AIE-related articles, and the growth rate was also lower than that of the other regions in mainland China, but higher than that of Europe and North America.

[10] The specific list of countries included in the Asia-Pacific region (excluding the Chinese mainland) is detailed in Appendix VI.
[11] See Appendix VI for a detailed list of countries in the European and North American regions.
[12] The global regions selected for comparison in this report include the Asia-Pacific (excluding the Chinese mainland), European, and North American regions.

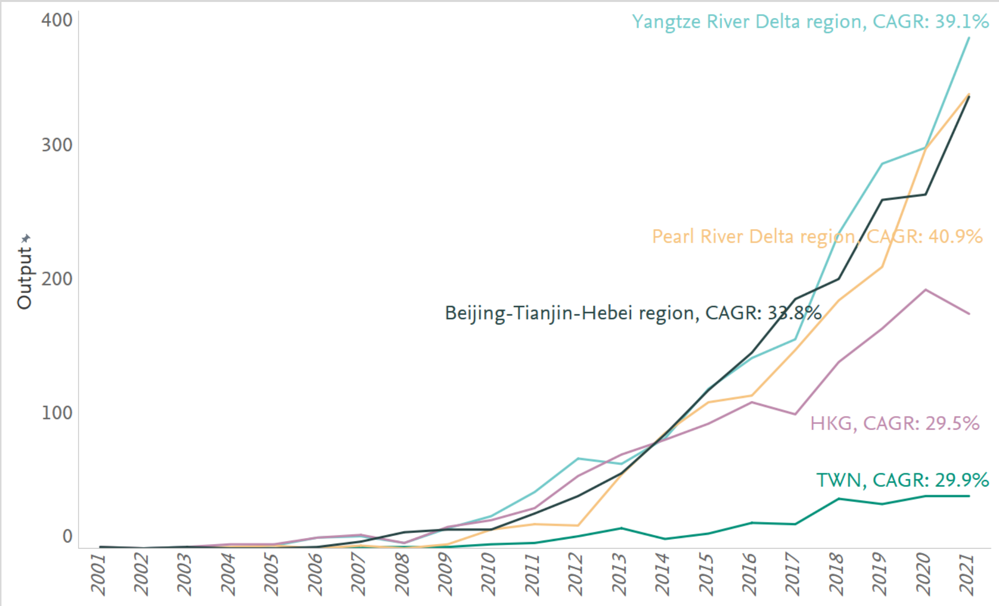

Figure 1.1.1.4 Comparisons of yearly trends in AIE research output for national regions[13] of China, 2001–2021 (China national region code: HKG-Hong Kong, China, TWN-Taiwan, China. CAGR indicates compound annual growth rate, see Appendix V for details)

II. Scholarly impact

To a certain extent, the impact of scientific research can be assessed by quantitative indicators such as the "citation count"[14]. Citation counts can reflect the scholarly impact of a publication. However, citation counts are subject to bias from factors such as the publication time, article type, and varying characteristics across different subject areas. Therefore, to permit comparisons across research fields, this report mainly uses the normalized "field weighted citation impact" (FWCI) to assess scholarly impact.

Despite some limitations, FWCI reflects the scholarly impact of the evaluated subject's publications. It is calculated by comparing the number of citations a publication receives with the number of citations expected for a publication of the same publication year, type, and subject; this can, thus, better circumvent the differences in the number of citations due to variations in publication size and citation characteristics by subject areas and by publication years. If the FWCI is 1, it means that the number of citations received by the evaluated subject's publication(s) is the same as what would be expected based on the global average for the same type of publication.

As shown in Figure 1.1.2.1, the FWCI of global AIE-related articles is 1.9, signifying that the number of citations of AIE-related articles is 1.9 times the global average. The value implies that research in this field has a high scholarly impact. With a relatively smaller output volume, Singapore has the

[13] The national regions selected for comparison in this report include the Yangtze River Delta region; Beijing-Tianjin-Hebei region; Pearl River Delta region; Hong Kong, China; and Taiwan, China.

[14] See Appendix V for details on the FWCI indicator elaboration and calculation.

highest scholarly impact (FWCI of 3.7) among the benchmarked countries, followed by the United States, China, and the United Kingdom with FWCIs of 2.2, 2.1, and 2.1, respectively, all of which are higher than the global average in the AIE field. All other countries have FWCIs between 1.3 and 1.9. India has an FWCI of 1.3, which is below the global average in the AIE field.

In terms of average citations per publication, Singapore also ranked the highest compared to other countries, with 77.7 citations per article. Singapore is followed by the United States and China, with 45.5 and 36.7 citations per publication, respectively, both higher than the global average in the AIE field (34.5 citations per article). South Korea has the fourth-highest average citations per article (33.7 citations per article), while other countries land between 19.5 and 33.5. Although the citations per article value for India is only 19.5, it is above the global average across all disciplines (17.4 citations per article), indicating that AIE research receives relatively higher attention in the global research field.

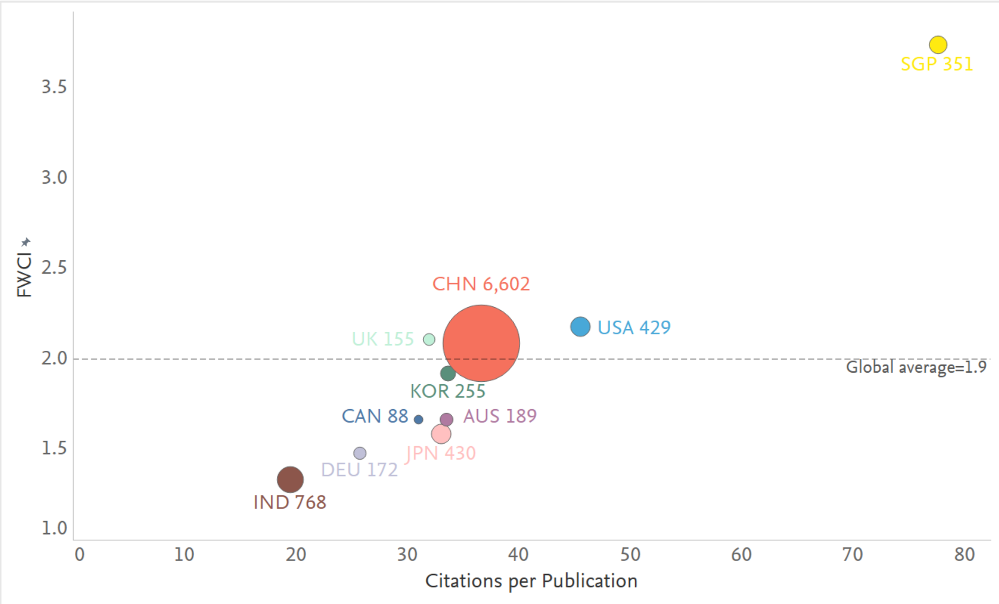

Figure 1.1.2.1 Citations per publication, publication count, and FWCI of publications in the field of AIE for the benchmarked countries and the world, 2001–2021. (The size of the bubble indicates the publication volume of the particular country; the larger the bubble, the higher the publication volume) (Country code: AUS-Australia, CAN-Canada, CHN-China, DEU-Germany, IND-India. JPN-Japan, KOR-Korea, SGP-Singapore, UK-UK, USA-USA, Global-Global)

Examining international regions, the Asia-Pacific region (excluding the Chinese mainland) has a relatively higher scholarly impact (as shown in the left panel of Figure 1.1.2.2) with an FWCI value of 2.3, which is slightly above that of China. North America follows with an FWCI value of 2.1, which is comparable to China's scholarly impact, both of which are higher than the global average (FWCI=1.9). The ranking of international regions by citations per publication is in line with their FWCI values. The Asia-Pacific region (excluding the Chinese mainland) has the highest number of citations per publication at 47.9, followed by North America and Europe at 42.8 and 27.5, respectively.

Among national regions, Hong Kong, China, has the highest scholarly impact of AIE scholarly output (as shown in the right panel of Figure 1.1.2.2), with an FWCI value of 3.3 and an average number of citations per publication of 76.7, which is second to Singapore among all the compared countries/regions. This is followed by the PRD region, with an FWCI value of 2.8. Compared to worldwide regions in the left panel, Hong Kong, China, and the PRD region have a higher scholarly impact than the Asia-Pacific (excluding the Chinese mainland), European, and North American regions. The YRD (FWCI=2.2) and BTH (FWCI=2.2) regions have comparable FWCI and their citations per publication (YRD's is 40.1 and BTH's is 38.2) are on par with those of China and North America, as well as above the global average in the AIE field. Together, this indicates that the scholarly impact of the TRD and BTH regions' AIE scholarly output is relatively similar. Taiwan, China ranks last among the national regions and its FWCI value (1.8) is lower than the global average in the AIE field. This is also the case for its average number of citations per publication, which is 24.1.

Figure 1.1.2.2 Citations per publication, publication count, and FWCI of publications in the field of AIE in China and global regions, 2001–2021 (left panel). Citations per publication, publication count, and FWCI of publications in AIE research in national regions of China, 2001–2021 (right panel). (The bubble size scales with the total output of a country/region. Region code: APAC-Asia Pacific region (excluding the Chinese mainland), EU-European region, NA-North America, HKG-Hong Kong, China, TWN-Taiwan, China)

III. The output of highly cited articles

The publication of highly cited articles reflects a subject's scholarly impact and is treated as indicative of excellence in research. In this section, a highly cited publication is defined as an article among the top 1% or 10% in the world, based on the FWCI values of all articles published in the same year, research field, and of the same publication type.

From 2001 to 2021, a cumulative total of 410 AIE publications worldwide were among the top 1% highly cited articles, accounting for 4.6% of all publications in the field; 2,883 were among the top 10% highly cited, making up 32.6% of all publications in the field. Both numbers are significantly higher than the global averages across all disciplines (1% and 10%, respectively). These numbers also indicate that the scholarly output in the field of AIE has high scholarly impact in general and garners interest in the scientific community.

Figure 1.1.3.1 shows that China has the highest output of highly cited articles among the top five countries by number of AIE publications. This is in line with its prolific output in the AIE field. Over the past two decades, China has accumulated 349 publications that are among the top 1% highly cited publications, accounting for 5.3% of all AIE publications in the country. China also has 2,347 publications among the top 10% highly cited publications, accounting for 35.5% of all its AIE publications. The share of highly cited publications in China outperformed that of the world, indicating that China's AIE output is of higher scholarly impact. Moreover, the number of highly cited articles in China is rapidly growing, which shows the country's continuous contribution of excellent research to the AIE field.

Apart from China, Singapore had the most highly cited articles, with a total of 46 top 1% highly cited publications and 228 top 10% highly cited publications (accounting for 65.0% of all AIE articles in Singapore) from 2001 to 2021. The data further confirms Singapore's high level of scholarly output and impact in the field. India and the US showed fluctuating growth in the amount of highly cited articles. From 2001 to 2021, India published a total of 171 top 10% highly cited articles, with the largest output of highly cited articles in 2021; the United States had a total of 151 top 10% highly cited articles, with the largest yearly output of 22 in both 2019 and 2021; Japan published 122 top 10% highly cited articles in total, with the largest output in 2017.

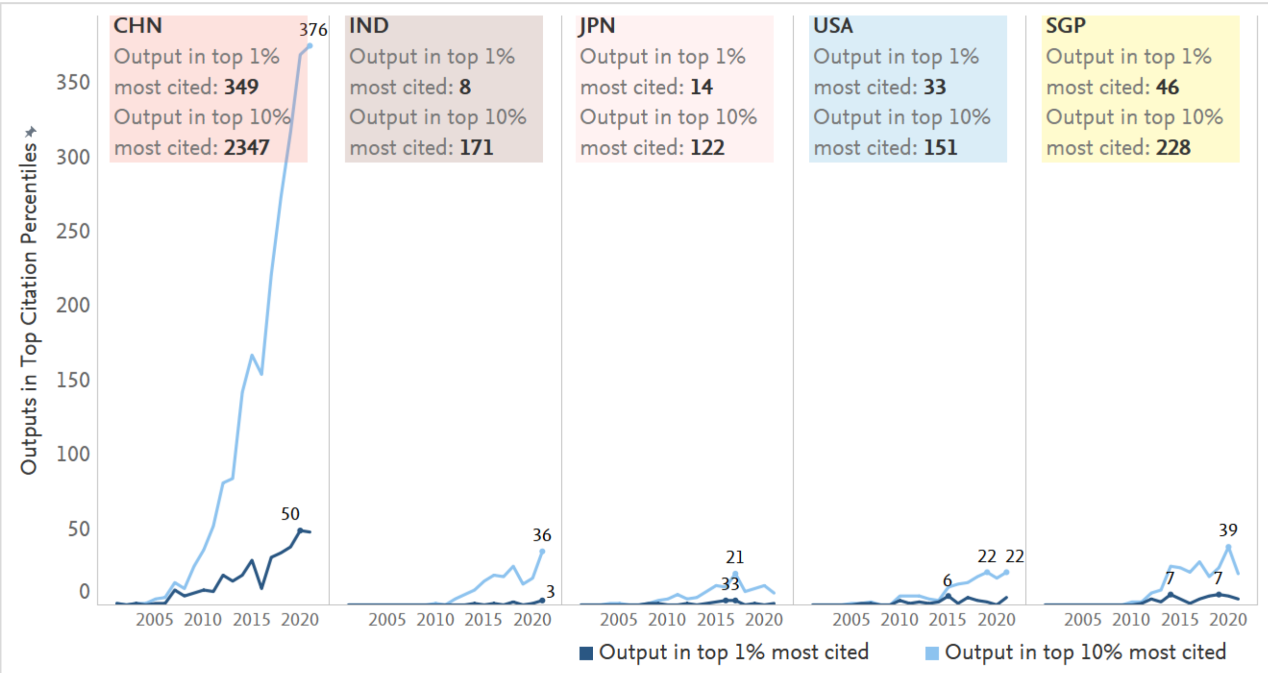

Figure 1.1.3.1 Top 1%/10% highly cited articles in the field of AIE for China and other benchmarked countries, 2001–2021. (The numbers in the line graph represent the highest yearly number of highly cited articles for each country over the years) (Code: CHN-China, IND-India, JPN-Japan, SGP-Singapore, USA-USA)

At the national level in China, the number of highly cited articles in each region increased in general from 2001 to 2021 (as shown in Figure 1.1.3.2). Hong Kong, China, and the PRD region had a relatively high output of top 1% highly cited articles, with 164 and 143 articles in the world's top 1%, respectively. BTH and YRD regions showed similar trends of the top 1% of highly cited articles.

The BTH region and Hong Kong, China showed similar trends in the growth of top 10% highly cited articles, with 644 and 687 publications among the world's top 10% highly cited, respectively; the level of top 10% highly cited articles for both the PRD and YRD regions grew rapidly after 2016. The level of highly cited articles in Taiwan, China, was relatively small, with 11 and 64 articles among the world's top 1% and top 10% highly cited from 2001 to 2021, respectively.

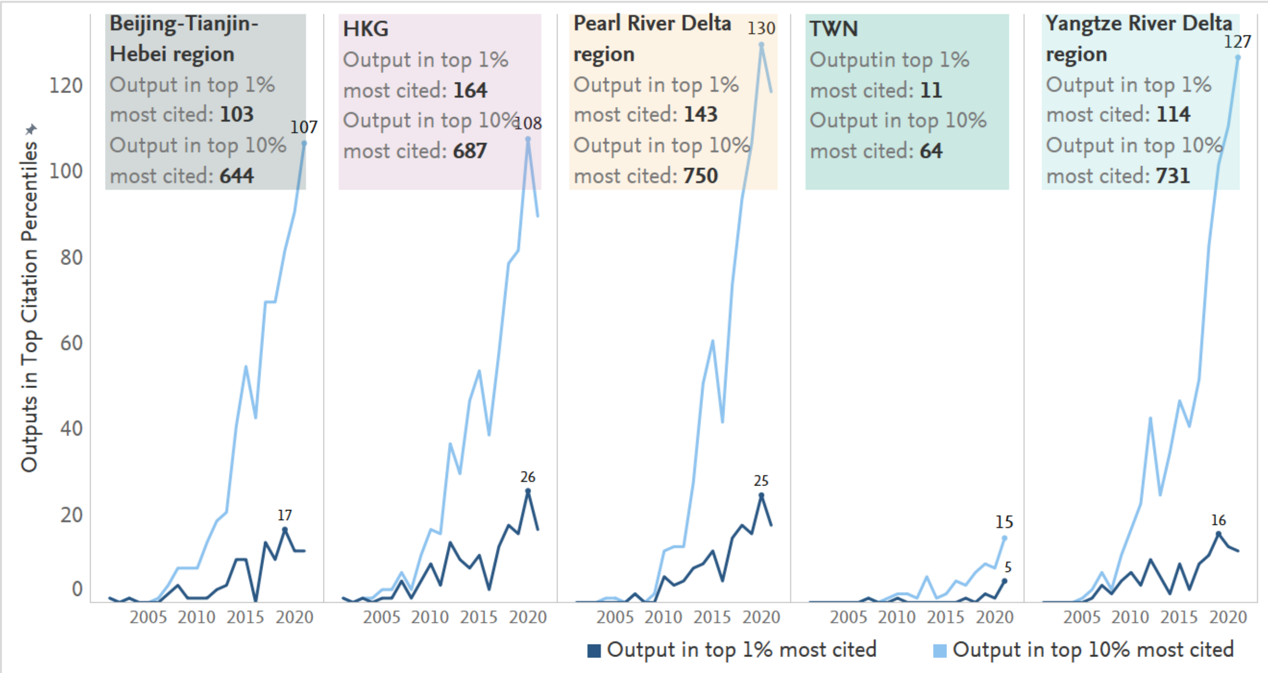

Figure 1.1.3.2 Top 1% and 10% highly cited articles in the field of AIE by national regions in China, 2001–2021. (The numbers in the line graph represent the highest yearly number of highly cited articles by regions over the years) (Code: HKG-Hong Kong, China, TWN-Taiwan, China)

Number and geographical distribution of AIE researchers

Talented researchers are one of the most important driving forces of scientific research. Researchers are valuable human capital for scientific institutions and play a crucial role in advancing science and technology. Understanding the population distribution of researchers will provide appropriate strategies for talent recruitment and training.

This section assesses the performance of China and other countries in terms of the number of researchers who authored AIE-related publications. Three different types of authors—coauthors, corresponding authors, and active authors[15]—are analyzed.

Analysis of AIE authors and their countries of affiliation shows that:

Over the past two decades, an increasing number of researchers have conducted, or were involved in, AIE-related work. Just as China is a leading contributor to the AIE field, Chinese authors also predominate this area, accounting for 70% of all authors in the field. The number of authors from other countries has also grown over the past two decades, with India showing the fastest growth.

Most countries tend to publish research collaboratively with multiple authors. In terms of the average number of authors per publication, the average in the global field of AIE was 6.4 from 2012 to 2021. Hong Kong, China, has the highest average number of publications per author, with an average of 2 AIE-related articles per author.

I. Changes among researchers in the AIE field

Over the past two decades, a total of 23,900 authors have published AIE-related research and the number of authors publishing AIE-related articles worldwide[16] continued to grow (as shown in Figure 1.2.1.1), from 11 in 2001 to 7,713 in 2021[17] and with a compound annual growth rate (CAGR) of 38.8%. The curved trendline of annual change in the number of authors shows that the global number of authors in the AIE field grew faster in the latter decade than the former; there was an average annual increase of 41 authors from 2001 to 2011 and an average increase of 704 from 2012 to 2021.

[15] See the text of sub-section II of this section for the definition of active author
[16] As long as the author's name appears in the article's author byline, that author will be counted as the author of an article
[17] This data is based on the Scopus database for the number of authors, with a small margin of reasonable error

The growth in the number of authors in other countries is consistent with the global trend: all showed rapid growth in the latter decade. China, as the leading contributor to the field, had the largest number of authors and the number was growing at a rapid rate, from 11 in 2001 to 5,696 in 2021, with a CAGR of 36.7%. India was also seeing consistent growth in the number of authors, from breaking into the double digits in 2012 to having 468 authors in 2021, with a CAGR of 43.6%. Korea has also witnessed a growth trend in the number of authors, ranking third with a CAGR of 30.0%, followed by Singapore and Japan, with CAGRs of 29.2% and 27.9%, respectively.

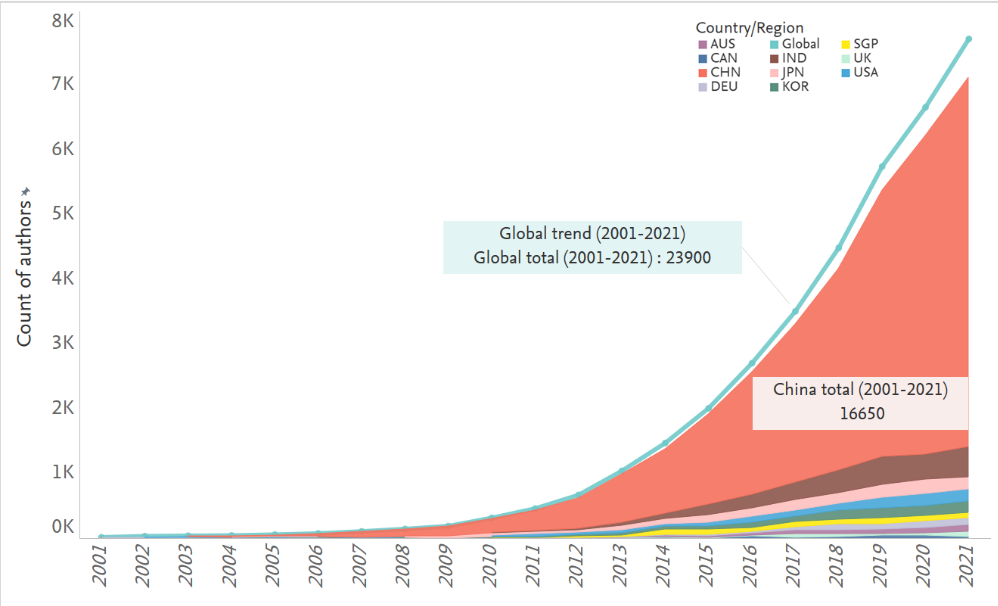

Figure 1.2.1.1 Annual trend in the number of authors involved in AIE-related publication globally and in benchmarked countries, 2001–2021

China had the highest number of authors in the field of AIE, with a total of 16,650 authors from 2001 to 2021 (as shown in Figure 1.2.1.2), accounting for 69.7% of all AIE researchers worldwide. India, Japan, and the United States also have a relatively high number of authors among the benchmarking countries, with a total of 1,643, 944, and 887 authors, respectively. These countries are also the top five countries with the most AIE publications. Other countries with high author count in the AIE field are Korea, Germany, Singapore, Australia, the UK, and Canada. Among them, Singapore, which ranked fifth in AIE output, has 363 authors, ranking seventh among all benchmarked countries and indicating that the figure of publications per author is relatively high.

In terms of average number of publications per author, Singapore ranks first with 1.0 publication per researcher; the UK and Australia both have 0.7 publications per author; the United States, India, Canada, and Japan all have 0.5 publications per author, while the average number of publications per author in China is comparable to that in Korea and Germany at 0.4. The data shows that there is extensive scientific collaboration within the AIE field, and that the collaborations are likely with researchers in other fields, indicating that AIE is an interdisciplinary field.

In terms of the average number of authors per publication, the average in the global field of AIE was 6.4 from 2012 to 2021, implying that, on average, 6–7 researchers co-authored an AIE publication. The data indicates that research in the field of AIE tends to be published as a collaboration between multiple authors. The average number of authors per publication in China is 6.9, which is higher than the global average in the AIE field. In China, the average number of authors per publication has also been increasing in the past decade, from 6.0 authors per publication in 2013 to 7.2 in 2020, indicating an increase in the number of researchers in the AIE field. There has also been an influx of young scientists joining research teams and the scale of research collaboration is gradually expanding.

Considering the institutions that the researchers are affiliated with, the average number of institutions per publication in the global field of AIE in the last decade was 2.2, implying that, on average, there were researchers from approximately 2–3 institutions involved in a collaborative publication. The average number of institutions per publication in China is 2.3, similar to the global average in the AIE field, and this has been fluctuating between 2.1 and 2.4 in the last decade. The data shows that in the last decade, AIE research has maintained its level of cross-institutional scientific collaboration.

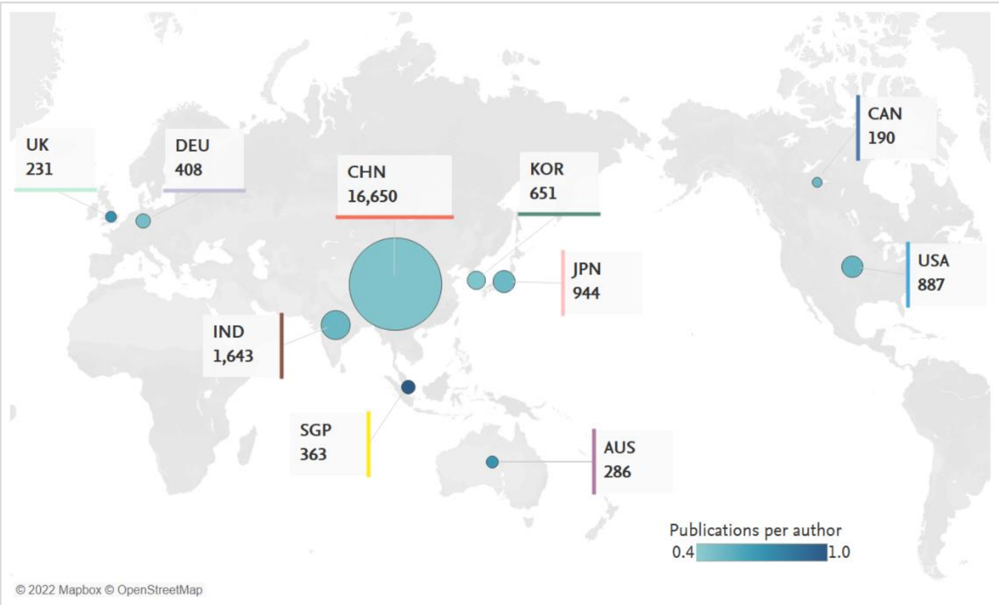

Figure 1.2.1.2 Comparison of the total number of AIE authors and average publications per AIE author in China and benchmarked countries, 2001–2021. (Codes: AUS-Australia, CAN-Canada, CHN-China, DEU-Germany, IND-India, JPN-Japan, KOR-Korea, SGP-Singapore, UK-United Kingdom, USA-United States)

Globally, the Asia Pacific region (excluding the Chinese mainland) had the fastest growing number of authors (as shown in the left panel of Figure 1.2.1.3), with an increase from 8 in 2001 to 1,404 in 2021 and a CAGR of 29.5%. From 2001 to 2021, a total of 5,011 authors from the Asia Pacific Region (excluding the Chinese mainland) published AIE-related research. This is followed by Europe and North America with 1,977 and 1,075 authors, with CAGRs of 23.2% and 17.4%, respectively.

Among the national regions, the YRD region has the largest and the fastest growing number of authors (as shown in the right panel of Figure 1.2.1.3), with 4,258 authors that published AIE-related articles over the last two decades and a CAGR of 38.3%. This is followed by the BTH and PRD regions with 3,269 and 1,947 authors, respectively. Hong Kong, China, has the fourth highest number of authors, with 602 that published AIE-related publications, but the growth rate is relatively low, with a CAGR of 17.4%. Taiwan, China, has the lowest number of authors in the field, with 449 authors over the last two decades and a CAGR of 25.9%.

It is worth mentioning that Hong Kong, China, has the highest average publications per author among all compared regions, with 2.1 publications per author, higher even than Singapore, which has the highest average publications per author at the country level. In other benchmarking regions, the average publications per author is mostly between 0.4 and 0.8. While this value for BTH, YRD, and Taiwan, China is 0.5, which is comparable to 0.4 in the EU, it reaches up to 0.8 in the PRD.

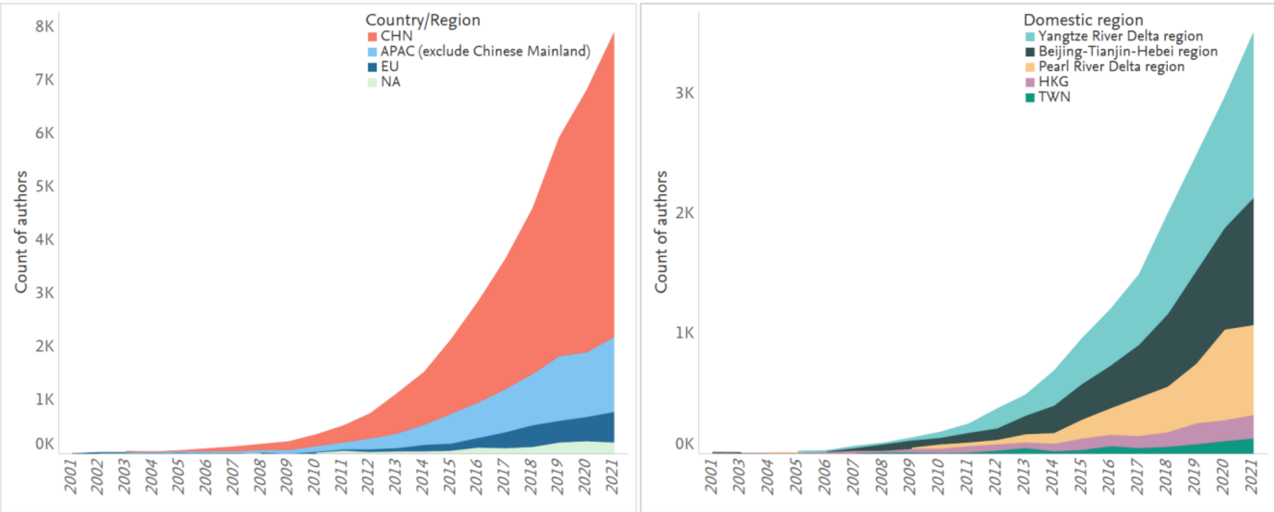

Figure 1.2.1.3 Trends in the number of authors publishing AIE-related articles in global regions (left panel) and in China by region, 2001–2021. (Codes: APAC-Asia Pacific (excluding the Chinese mainland), EU-Europe, NA-North America, HKG-Hong Kong, China, TWN-Taiwan, China)

II. Corresponding author and active author performance (2012–2021)

Corresponding authors are often considered the people primarily responsible for research and the point of contact for a publication. They are usually senior researchers or group leaders who play a key role in initiating, designing, and conducting the studies. In later stages of the research, they guide the development and revision of the manuscript for publications. Corresponding authors referred to in this report are those who have published at least one Scopus-indexed AIE paper as a corresponding author from 2012 to 2021.

Active authors are defined as authors who have published at least 10 Scopus-indexed publications since 2001, or those with at least one Scopus-indexed publication in the last five years (2017–2021). The minimum threshold set for AIE scholarly output by an author helps identify core researchers that are active in the AIE field.

The number of corresponding and active authors among the benchmarked countries shows (Figure 1.2.2.1) that China has far more corresponding and active authors than other countries do. The data is consistent with the analyses that show China accounts for a large percentage of publication output and the total number of authors worldwide in AIE research, which further demonstrates China's major contribution to the field. Following in ranked order, the number of active authors in India, Japan, and the United States are 1,396, 676 and 631, respectively. These countries' rankings are in line with their ranking in total number of publications. Singapore, which ranks fifth by publication output, has a lower number of corresponding and active authors, with only 49 corresponding authors and 266 active authors from 2012 to 2021. Meanwhile, Korea has the fifth-highest number of corresponding and active authors in the field of AIE, with 103 and 512, respectively.

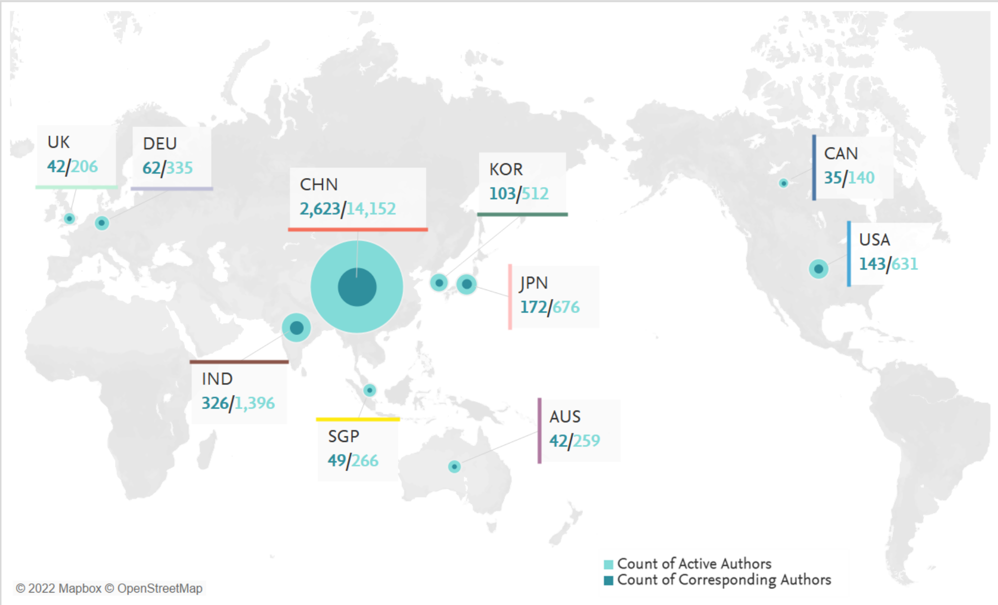

Figure 1.2.2.1 Total number of corresponding authors versus total number of active authors in the AIE field by countries, 2012–2021. (Codes: AUS-Australia, CAN-Canada, CHN-China, DEU-Germany, IND-India, JPN-Japan, KOR-Korea, SGP-Singapore, UK-UK, USA-US)

Leading research institutions

Scientific research institutions can be higher education institutions or research institutes. They are the backbone of a country's science and technology capabilities for strategic planning and competition that eventually leads to innovation. Scientific research institutions not only undertake the task of fostering cutting-edge research, technology transfer, and technology service, but they also shoulder the responsibility of training the workforce and laying the groundwork for scientific innovation. Therefore, locating and assessing leading research institutions in the field can help guide research institutions to reach the national goals and improve their competitiveness. Understanding the institutions can also help establish incentive systems and management models, allocate research funding and build scientific workforce, further enhancing the infrastructure and development of science.

This subsection focuses on the leading research institutions in the field of AIE worldwide and provides a comparative analysis on scholarly output and impact.

Analysis of leading scientific institutions shows that:

There is a concentration of research institutions publishing in the AIE field: the 10 institutions that published the most AIE research globally produced 36.8% of the total publications in the field. At the same time, 9 out of the top 10 publishing institutions are from China. From a global perspective, the Hong Kong University of Science and Technology (HKUST) and South China University of Technology (SCUT) are the two institutions with the highest number of publications in this field.

Among the major publishing institutions in other countries, the National University of Singapore (NUS) is the most prolific in the field and is also the only non-Chinese institution among the top 10 contributors to AIE research.

I. Top 10 institutions in AIE in terms of number of publications or total citations

The top 10 institutions by publication output and citation count of AIE articles globally from 2001to 2021 are shown in Figure 1.3.1.1. Nine of the top 10 institutions by publication output are from China, and eight of the top 10 institutions by citation count are also from China. Among them, HKUST and SCUT have the highest number of AIE publications. They are the only institutions with more than 1,000 publications, numbering at 1,185 and 1,052 AIE-related publications, respectively. The Chinese Academy of Sciences (CAS) ranks third, with 755 publications.

The top three institutions above also rank as the top three in citation count. Zhejiang University and the NUS are in the fourth and fifth place, respectively. Jilin University, which has a relatively high number of publications, places sixth, with a relatively low total citation count. The Agency for Science, Technology and Research (A*STAR), Singapore, ranks twentieth in the number of publications but has a relatively high number of total citations, ranking eighth.

From the perspective of highly cited publications, the top three institutions in publication output are also the top three institutions with most highly cited articles. The institutions include the HKUST, which produced 162 top 1% highly cited articles and 653 top 10% highly cited articles (including the top 1% highly cited articles) during 2001–2021. SCUT has produced 522 top 10% highly cited articles and 107 top 1% highly cited articles. In addition, NUS, which ranks seventh in publication volume, has a large output of highly cited articles. It ranks fourth among the top 10 institutions with the most top 10% highly cited articles.

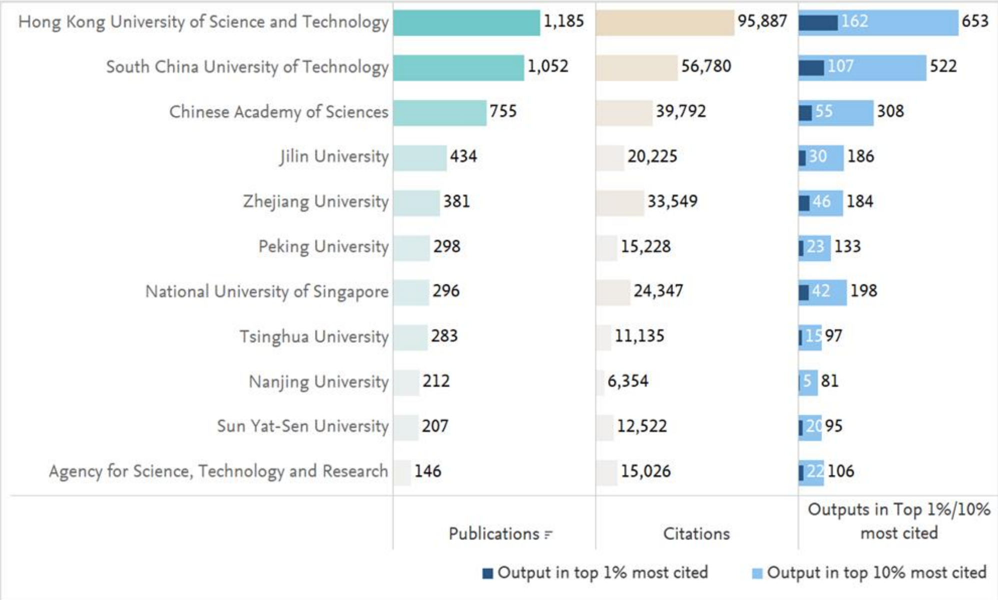

Figure 1.3.1.1 The top 10 institutions with the highest scholarly output or total citations in the AIE field globally, 2001–2021.

II. Top 10 Chinese institutions by publication output in AIE research (2012–2021)

China is the major contributor of articles in the AIE field. A comparative analysis of Chinese research institutions with a high number of AIE-related publications further showcases China's research performance in the field. As shown in Figure 1.3.2.1, the top five Chinese institutions with the highest output from 2012 to 2021 are in line with the top five institutions with the highest output from 2001 to 2021 worldwide. In China, HKUST has the most publications in the field, ranking first in terms of number of publications, total citations, and highly cited articles. The university produced 1,090 AIE-related publications in the last decade, of which 134 were in the top 1% highly cited and

590 in the top 10% highly cited. It is followed by SCUT, CAS, Jilin University, and Zhejiang University with 1,046, 713, 402, and 305 publications, respectively. Compared to Figure 1.3.1.1 above, it shows that AIE-related publications from Chinese institutions with high scholarly output were mainly produced in the last decade.

The top five institutions with the highest citation count are the same as institutions with the most publications, which indicates the strength of these institutions in the field of AIE. Huazhong University of Science and Technology ranked tenth in number of publications, but had a relatively high number of total citations, placing eighth, with a total of 199 AIE publications and 6,797 total citations in the last decade.

From the perspective of the number of highly cited articles, Peking University and Shenzhen University have relatively high numbers, besides the top five institutions with the most publications. The two universities both publish 110 of the top 10% highly cited articles, ranking sixth on the list.

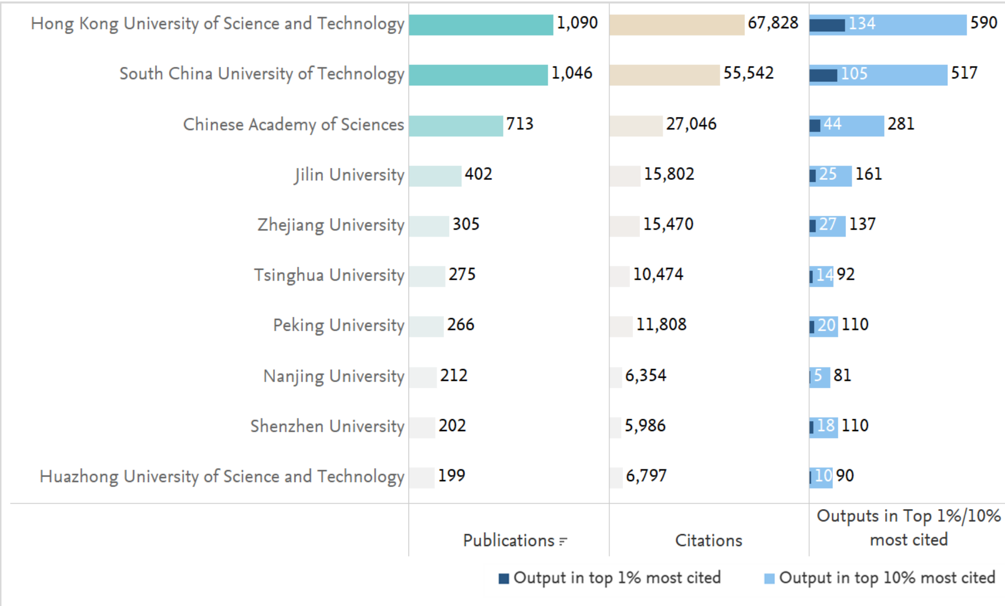

Figure 1.3.2.1 The top 10 institutions by scholarly output in the AIE field in China, 2012-2021.

III. Leading institutions in the top five countries with the highest number of publications in AIE research

Figures in previous sections have shown the dominant position of Chinese institutions in AIE research output. More information about high-output institutions in other countries can be seen in Figure 1.3.3.1, which lists the top five high-output academic institutions from countries with the most AIE publications, other than China; namely, India, Japan, the United States, and Singapore. The chart shows that little difference is found between the top five academic institutions in terms of the number of publications for India, Japan, and the United States.

Singapore's AIE publications are concentrated in the top two institutions. NUS ranks first among the high-output institutions from all of the compared countries, excluding China. From 2012 to 2021, the University produced 294 AIE-related publications, of which 42 were top 1% highly cited and 197 were top 10% highly cited. This number is comparable to the output of some Chinese institutions. A*STAR in Singapore ranks second with 144 publications. In third through to fifth place, Nanyang Technological University, Singapore University of Technology and Design, and Singapore National Eye Center, have 46, 19 and 3 publications, respectively, which are all less than 50.

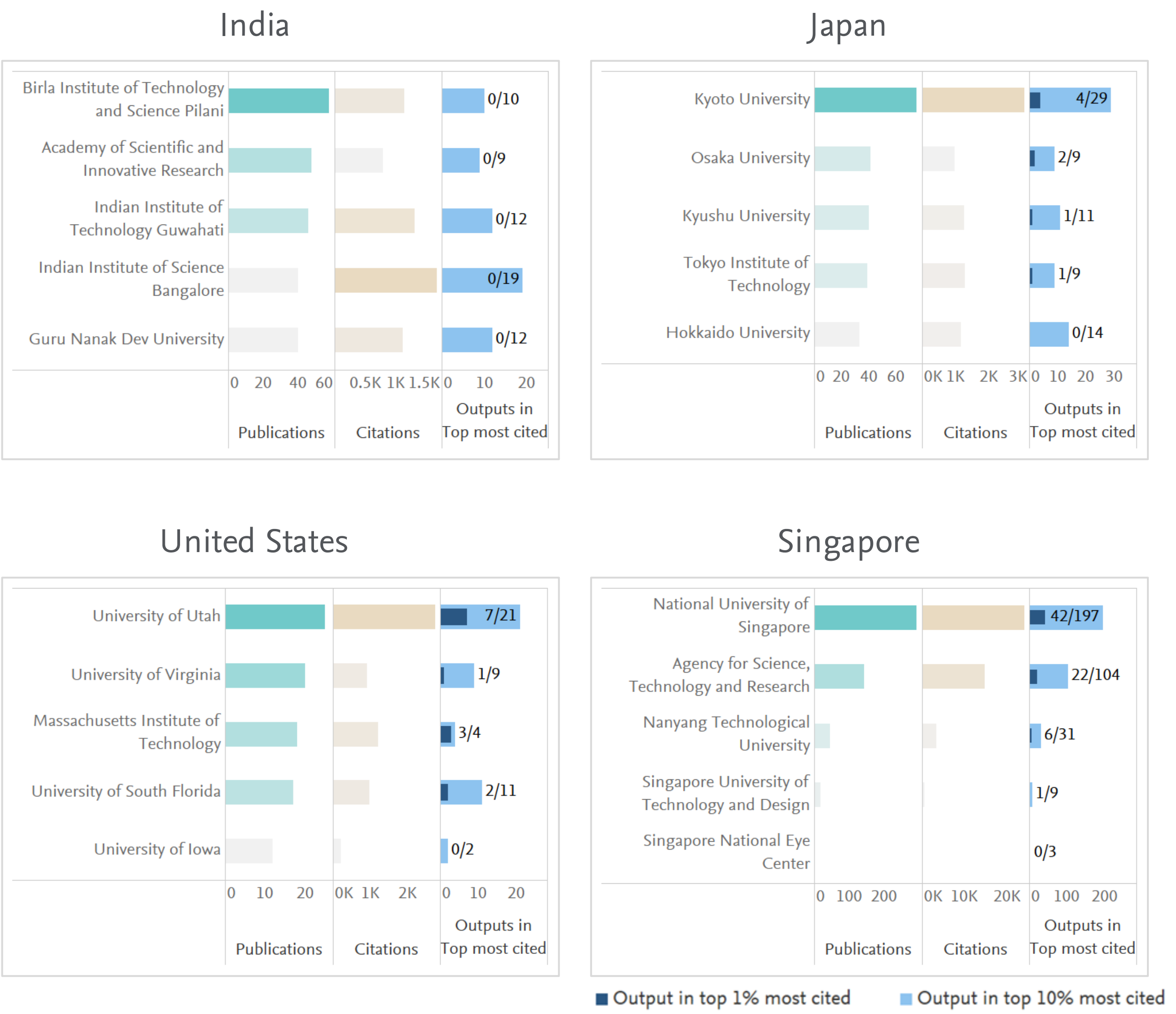

Figure 1.3.3.1 The top five academic institutions by scholarly output in the field of AIE in India, Japan, the United States, and Singapore, 2012–2021.

The top five contributors in India are: Birla Institute of Technology and Science Pilani, Academy of Scientific and Innovative Research, Indian Institute of Technology Guwahati, Guru Nanak Dev University and Indian Institute of Science Bangalore, with 58, 48, 46, 40 and 40 AIE-related publications, respectively. Among these, Indian Institute of Science Bangalore has the highest number of highly cited articles, with 19 in the top 10% of highly cited articles.

In Japan, the most prolific contributor to AIE research is Kyoto University, ranking third among all institutions in the compared countries, except China, with 75 publications and 29 of which are in the top 10% highly cited list. This is followed by Osaka University, Kyushu University, Tokyo Institute of Technology, and Hokkaido University with 41, 40, 39, and 33 AIE-related publications, respectively.

The top five institutions in the US, by number of AIE-related publications, are: University of Utah, University of Virginia, Massachusetts Institute of Technology, University of South Florida, and the University of Iowa, with 25, 20, 18, 17, and 12 publications, respectively. The institution with the most highly cited articles is the University of Utah, with 21 publications among the top 10% list of highly cited articles. This institution also has the largest share of highly cited articles (84%) among the top five institutions in the United States.

Chapter 2

Overview of AIE research collaboration

Key data

41.2% and 1.7

National collaboration rate (above the global average of 31.2%) and corresponding FWCI of AIE-related publications (2012–2021)

27.6% and 2.6

International/regional collaboration rate (above the global average of 19.5%) and corresponding FWCI of AIE-related publications (2012–2021)

43.2% and 1.8

National (within the Chinese mainland)[18] collaboration rate and corresponding FWCI of China's AIE-related publications (2012–2021)

30.9% and 2.8

Offshore collaboration rate[18] and corresponding FWCI of China's AIE-related publications (2012–2021)

Hong Kong University of Science and Technology

The institution that has the most AIE-related publications that are international/regional (including the Chinese mainland) collaborations, producing 1,071 collaborative publications (2012–2021)

Chinese Academy of Science

The institution that has the most AIE-related publications that are national collaborations, producing 508 collaborative publications (2012–2021)

South China University of Technology

Institution with the most extensive collaboration with HKUST, co-authoring 796 publications (2012–2021)

National Natural Science Foundation of China

Funding agency that supported the most AIE-related publications, funding a total of 4,192 publications (2012–2021)

[18] In this chapter, the national collaboration for China is specifically referred to as national (within the Chinese mainland) collaboration, as this type of collaboration of China excludes mainland China's collaboration with the Hong Kong Special Administrative Region, the Macau Special Administrative Region and Taiwan Province, which are sovereign of the People's Republic of China. For the same reason, the international/regional collaboration for China is specifically referred to as offshore collaboration, as this type of collaboration includes mainland China's collaboration with areas mentioned above.

Research collaboration and funding

As knowledge of science deepens, complex questions arise. Answering these questions often requires researchers from different areas and regions to share knowledge and resources. Different forms of scientific collaboration not only facilitate the flow and sharing of knowledge but also stimulates innovation and provides new perspectives in research. Moreover, collaboration on scientific research between different regions and countries often leads to a wider academic and social impact than independent research alone does. This is why research collaboration is an important metric for measuring research development.

This subsection focuses on collaborative publications in AIE-related articles from 2012 to 2021. Based on the number of authors at the time of publication and their affiliations, the report categorizes collaborative publications into four categories: international/regional collaboration, national collaboration, institutional collaboration, and independent research[19]. The categorization is a way to analyze and benchmark the performance, trends, and major players in collaborative publications in the AIE field.

Analysis of the performance of research collaboration shows that:

In China, collaborations in the field of AIE research are mainly national (within the Chinese mainland)[20], but Hong Kong, China, has a 98% international/regional (including the Chinese mainland) collaboration rate. The international/regional collaboration rate is also high in the United States and Singapore, both reaching 77%. From the perspective of scholarly impact, the FWCI of international/regional collaborations is higher than national collaborations at present, indicating that enhancing international/regional research collaboration may help to expand the impact of AIE research in the international community.

The Hong Kong University of Science and Technology (HKUST) has the highest number of publications in the AIE field that were international/regional (including the Chinese mainland) collaborations, and the Chinese Academy of Sciences (CAS) has the highest number of national collaborations in the AIE field.

[19] See Appendix V for detailed definitions of the types of collaboration.

[20] Chinese mainland here refers specifically to the territory of the People's Republic of China other than the Hong Kong Special Administrative Region, the Macau Special Administrative Region and Taiwan Province, which are sovereign of the People's Republic of China.

I. Overall performance of AIE-related collaborative research

i. Share of different types of scientific collaboration

For the period 2012–2021, China accounted for 75.0% of the global AIE output, and China's AIE publications were mainly based on national (within the Chinese mainland)18 collaboration (43.2%). This explains national collaboration as the main form of research collaboration in the global AIE field. For the period 2012–2021, a total of 3,491 publications were published by authors from different institutions in the same country or region, accounting for 41.2% of global AIE publications. The second-most common type of collaboration was institutional collaboration, with a total of 2,543 publications by different researchers from the same institution, accounting for 30.0% of global AIE publications. The international collaboration rate of AIE-related publications was 27.6%, with a total of 2,338 publications produced with trans-national or cross-regional collaboration.

According to the distribution of the types of research collaboration in AIE-related publications from 2012 to 2021 (Figure 2.1.1.1), China had the highest share of national collaborative publications among benchmarked countries, with a share of 43.2%. The number indicates that the country's research publications in the field are primarily collaborations between different institutions within the Chinese mainland[21], which also contribute to the high national collaboration rate in the world. Among the countries, publications in the US and Singapore are mainly international/regional collaborations, with a rate of 77%. India and Japan's AIE-related publications are dominated by institutional collaborations, with a rate of 48.2% and 42.4%, respectively. Two possibilities may explain the different patterns of research collaboration in China and other countries: first, it may be because of the nature of the research topics within the AIE field; second, it may be because the national funding of these countries for AIE research does not reach the level of China's. Therefore, other countries tend to seek out international collaboration in AIE research.

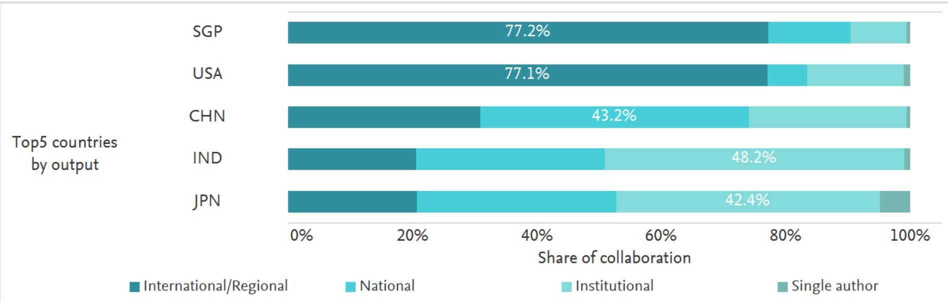

Figure 2.1.1.1 Different types of research collaboration and their output shares in the top 5 countries by output in the field of AIE, 2012–2021. (Code: CHN-China, IND-India, JPN-Japan, SGP-Singapore, USA-USA)

The types of research collaboration in national regions of China are shown in Figure 2.1.1.2. Research related to AIE in the Pearl River Delta (PRD) region is dominated by offshore collaboration[18]. Both Hong Kong, China, and Taiwan, China have a focus on international/regional

[21] Given the relatively different research and education systems in each region, research collaborations between Hong Kong, China; Macau, China; Taiwan, China; and the Chinese mainland are classified as international/regional (including the Chinese mainland) collaborations in the type of research collaboration in this report.

(including the Chinese mainland) collaboration in research that is related to AIE. Of the two, Hong Kong, China, has the highest rate of international/regional (including the Chinese mainland) collaboration in AIE-related publications, reaching 97.9%[21]. Only a small portion of the AIE-related publications from Hong Kong, China stems from intra-institutional collaboration in the region, which fully demonstrates the in-depth integration and mutual support between the universities in Hong Kong, China and the Chinese mainland. The offshore collaboration rate in the PRD region was 62.3%, and the rate of international/regional (including the Chinese mainland) collaboration for Taiwan, China was 55.1%. The Yangtze River Delta (YRD) and Beijing-Tianjin-Hebei (BTH) regions have a focus on national (within the Chinese mainland) collaboration, with a rate of 42.1% and 58.5%, respectively. This shows that the Pearl River Delta may have a geographical advantage in promoting cross-region cooperation.

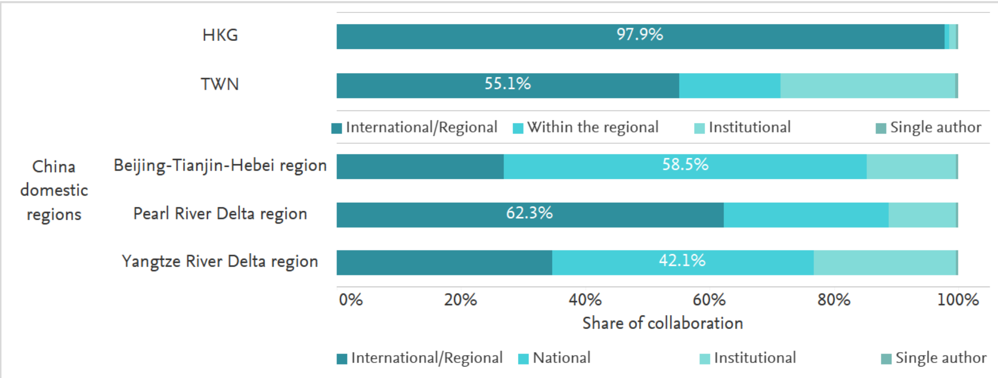

Figure 2.1.1.2 Share of four types of collaborative publications in the field of AIE by regions within China, 2012–2021. (Code: HKG-Hong Kong, China, TWN-Taiwan, China)

ii. Analysis of trends in AIE-related collaborative research in China

China is the main contributor to the field of AIE. This subsection analyzes the annual trend in AIE-related publications through the lens of offshore collaboration and national (within the Chinese mainland) collaboration in China. The trends are shown in Figure 2.1.1.3. From 2012 to 2021, China's share of national (within the Chinese mainland) collaborations in the field of AIE showed an increase, with the percentage of national (within the Chinese mainland) collaborations growing from 31.1% in 2012 to 49.1% in 2021. Compared to national (within the Chinese mainland) collaborations, the share of offshore collaboration was slightly lower and fluctuated between 28.1% and 39.9% in the same period. The offshore collaborations achieved their highest percentage in 2012 and their lowest in 2021. Despite that, the share has always been higher than the global average across disciplines (19.5%). The downward trend in the offshore collaboration rate may be due to gradual improvement in the level of domestic scientific research platforms and the return of talented academic researchers, which has strengthened national scientific research.

In terms of scholarly impact, the FWCI of China's offshore collaboration in AIE research in the past decade ranged from 2.0 to 4.5, which is higher than the average FWCI of the overall AIE publications (1.9). The FWCI of national (within the Chinese mainland) collaborations ranged from 1.5 to 2.9, which is relatively lower than the average FWCI of AIE publications. Overall, the scholarly impact of offshore collaborations is higher than that of national (within the Chinese mainland) ones, showing that AIE-related publications can benefit from international/regional or offshore collaboration to help increase their scholarly impact.

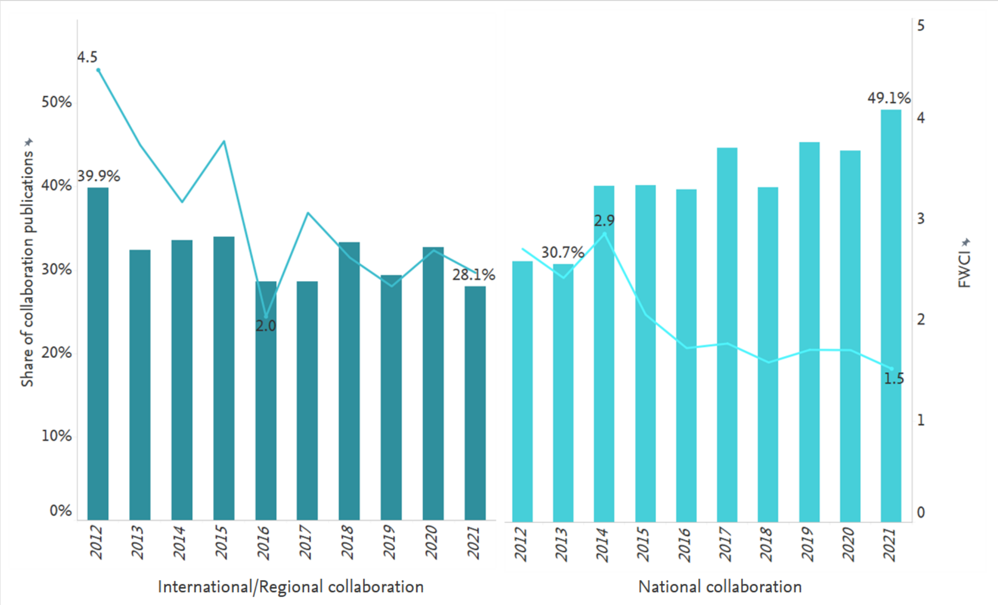

Figure 2.1.1.3 Share and scholarly impact of AIE publications with offshore and national (within the Chinese mainland) collaboration in China, 2012–2021. The bar represents the share of collaborative publications, and the line represents FWCIs.

II. Leading institutions in AIE research collaboration

As shown in Figure 2.1.2.1, the institutions with the highest number of international/regional[22] collaborations in the AIE field from 2012 to 2021 were HKUST and South China University of Technology (SCUT). The two institutions also have the highest publication output in AIE research, with 1,071 and 833 international/regional collaborations, respectively. They are followed by the National University of Singapore (NUS), Zhejiang University, and CAS, with 223, 204, and 203 publications, respectively.

In terms of the scholarly impact of international/regional collaborations of the top 10 institutions by relevant output, most institutions have an FWCI that is higher than 3.0, which is greater than the global average in the AIE field (FWCI of 2.6). International/regional collaborations from the Agency for Science and Technology Research (A*STAR), Singapore, has the highest scholarly impact among institutions, with an FWCI of 4.9, followed by the NUS with an FWCI of 4.2.

[22] For universities in Hong Kong, Taiwan, and Macau in China, the international/regional collaboration refers specifically to the international/regional collaboration (including the Chinese mainland); for Chinese mainland universities, the international/regional collaboration refers to international/regional collaboration (including Hongkong, Macau, and Taiwan in China).

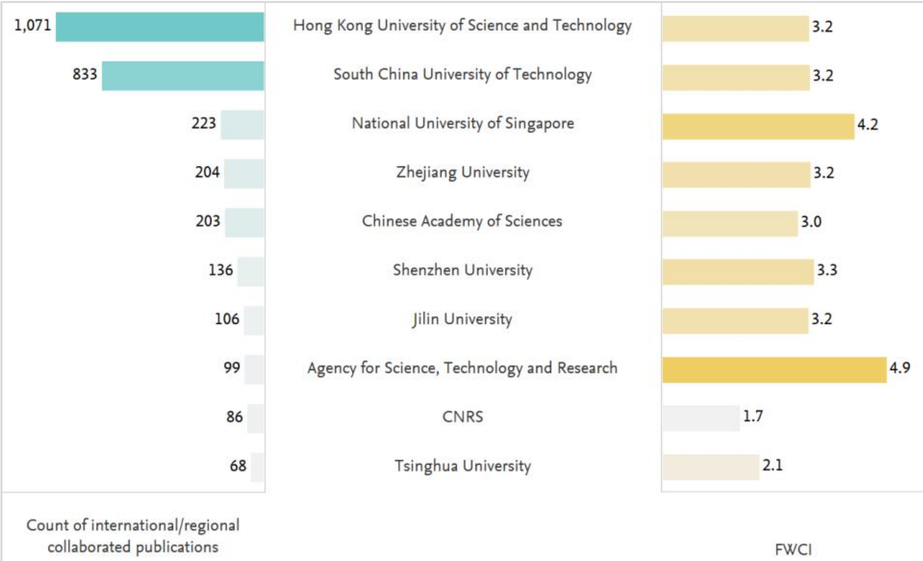

Figure 2.1.2.1 Top 10 institutions by international/regional collaboration output and scholarly impact in the field of AIE, 2012–2021. (CRNS: Centre national de la recherche scientifique)

In the last decade, the institution with the highest number of national (within the Chinese mainland) collaborations in AIE research is CAS (as shown in Figure 2.1.2.2), with 508 collaborative publications from 2012 to 2021. Peking University, Tsinghua University, SCUT, and the University of Chinese Academy of Sciences follow with 196, 174, 160, and 158 publications in the field, respectively.

From the perspective of the scholarly impact of national (within the Chinese mainland) collaborations, Wuhan University has the highest FWCI of 3.0, followed by Peking University, which has the second-most national (within the Chinese mainland) collaborations, with an FWCI of 2.5. Most of the FWCIs of national (within the Chinese mainland) collaborations from the rest of the institutions were higher than the global average in the field (FWCI of 1.7).

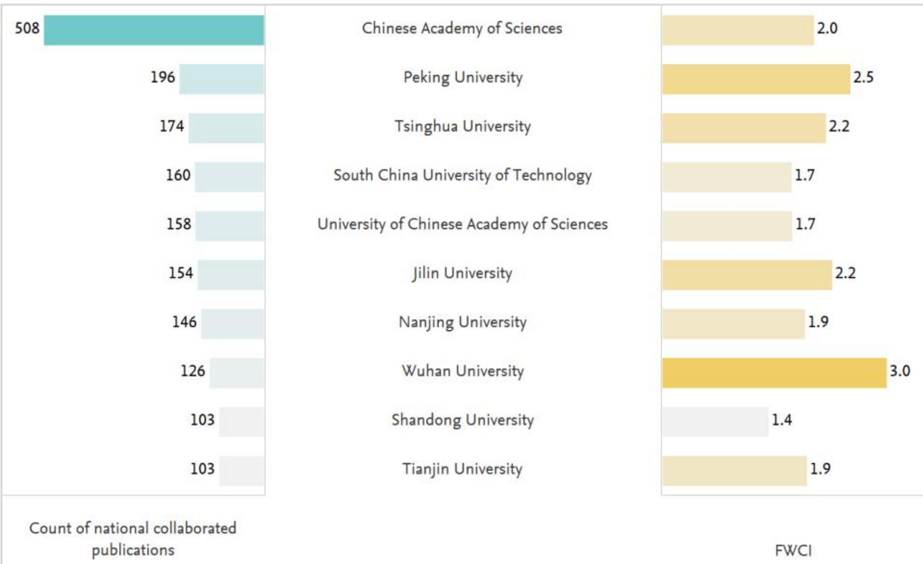

Figure 2.1.2.2 1 Top 10 institutions by national (within the Chinese mainland) collaboration output and their scholarly impact in the field of AIE, 2012–2021.

III. Funding and support

Research funding supports researchers in pursuing basic research and exploring cutting-edge science and technology. As an investment, funding is also essential for building research teams, training scientists and is one of the driving forces in scientific advancement. Quantifying research output through the number of publications that result from funding by a given agency is important for evaluating how these investments promote research development.

Most of the funding agencies and grant programs are from China, according to the funding information of all AIE-related publications from 2012 to 2021. Among the top 30 funding entities that supported the most publications, 76.7% are from China, including three agencies from Hong Kong, China. The National Natural Science Foundation of China (NSFC) funded the most publications, by an overwhelming margin, with 4,192 publications (see Figure 2.1.3.1). On the one hand, it reflects the sheer amount and scale of AIE-related publications in China, while on the other hand, it also demonstrates China's emphasis on AIE research. The investment from NSFC provided a strong support for basic research in the field of AIE. Following NSFC is the Ministry of Education of China, the Ministry of Science and Technology of China, and the Ministry of Finance of China, funding 547, 509, and 386 publications, respectively. Of note, this count is based on funding acknowledgments in the publications. Research in AIE also received funding from agencies in Japan, India, South Korea, Singapore, and the United States. The Society for the Promotion of Science and the Ministry of Education, Culture, Sports, Science and Technology from Japan funded 275 and 181 publications, respectively; the Indian Department of Science and Technology, the Indian Council of Scientific and Industrial Research and the Indian Science and Engineering Research Board funded 177, 176 and 142 publications, respectively. It is also important to point out that information about funding institutions comes only from the acknowledgment of the publication. It is important to keep in mind that an academic publication might not be the only form of output of the projects funded by the funding institution, and that the funding institution might not be properly acknowledged. The above ranking is for reference only and does not represent the actual level of funding and support of national governments through their funding agencies in the AIE research field.

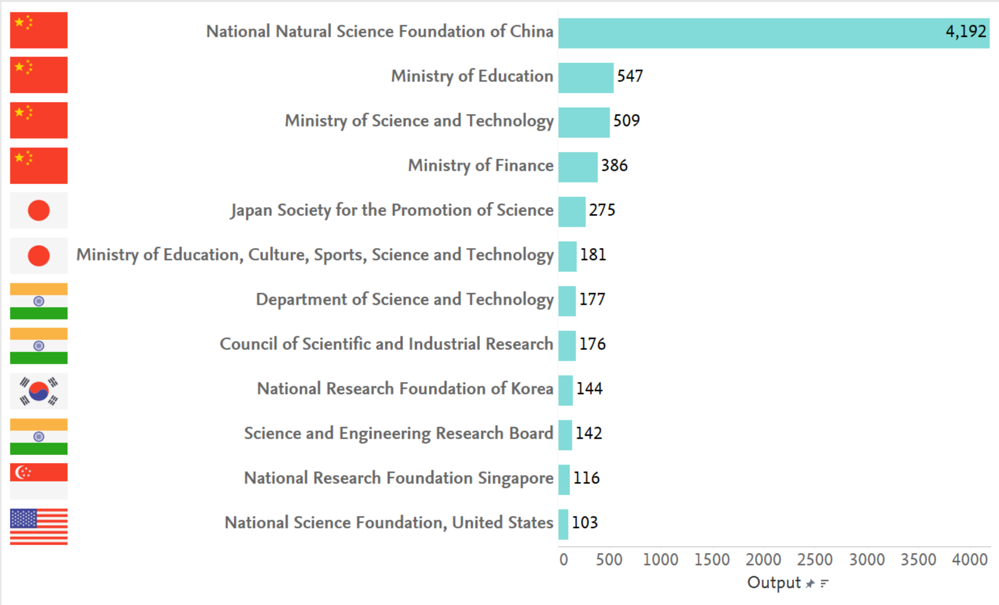

Figure 2.1.3.1 Top 12 government agencies that supported AIE research by publication output in the world, 2012–2021

Regarding the top 12 funding agencies by regions (see Figure 2.1.3.2), most of them were from China. Among them, funding agencies from Hong Kong, China, supported the largest number of publications. From 2012 to 2021, the Innovation and Technology Commission of Hong Kong supported a total of 365 AIE-related publications. Ranking second and third, the Natural Science Foundation of Guangdong Province and the Research Grants Council from Hong Kong funded 322 and 191 publications, respectively. In addition, the Chinese Academy of Sciences, NUS (National University of Singapore), UGC (University Grants Committee), and South China University of Technology have also promoted the development of this field in the form of scientific research funding.

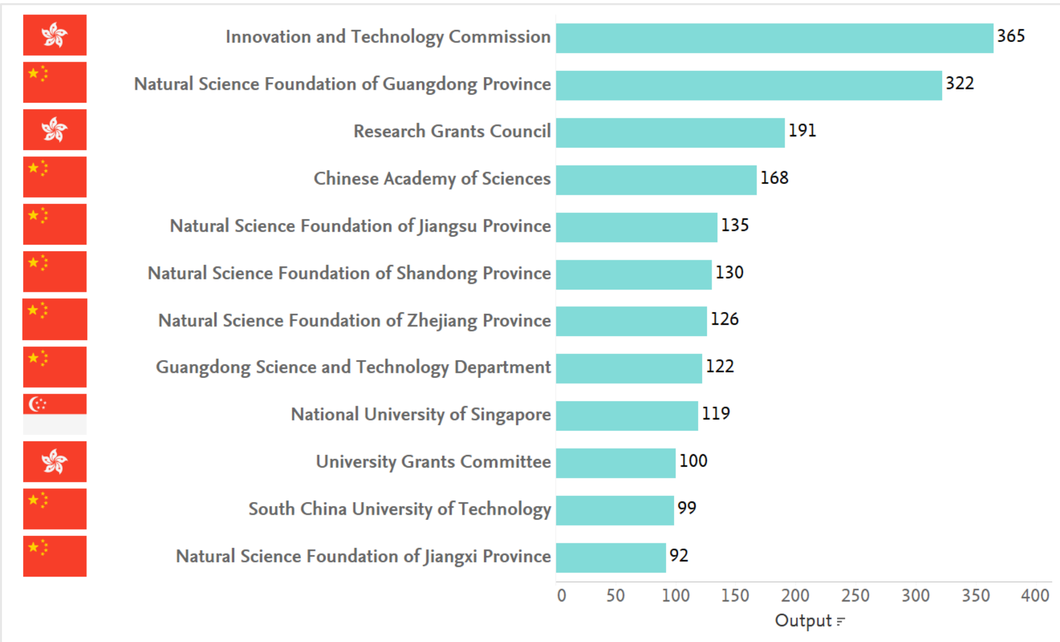

Figure 2.1.3.2 Top 12 funding agencies that supported AIE publications by publication output in regions, 2012–2021

From the perspective of grant programs (see Figure 2.1.3.3), grants that resulted in a higher number of publications were mostly from China. The Fundamental Research Funds for the Central Universities and the National Key Research and Development Program of China were the two programs that supported the most publications from 2012 to 2021. The programs funded 692 and 500 publications in the field of AIE, respectively. They were followed by the China Postdoctoral Science Foundation and the National Basic Research Program of China (973 Program), which funded 337 and 276 publications, respectively. Research in this field was also funded by province-led programs. The Priority Academic Program Development of Jiangsu Higher Education Institutions, Science and Technology Planning Project of Guangdong Province, and Guangdong Province Introduction of Innovative R&D Team funded 114, 94, and 68 publications, respectively.

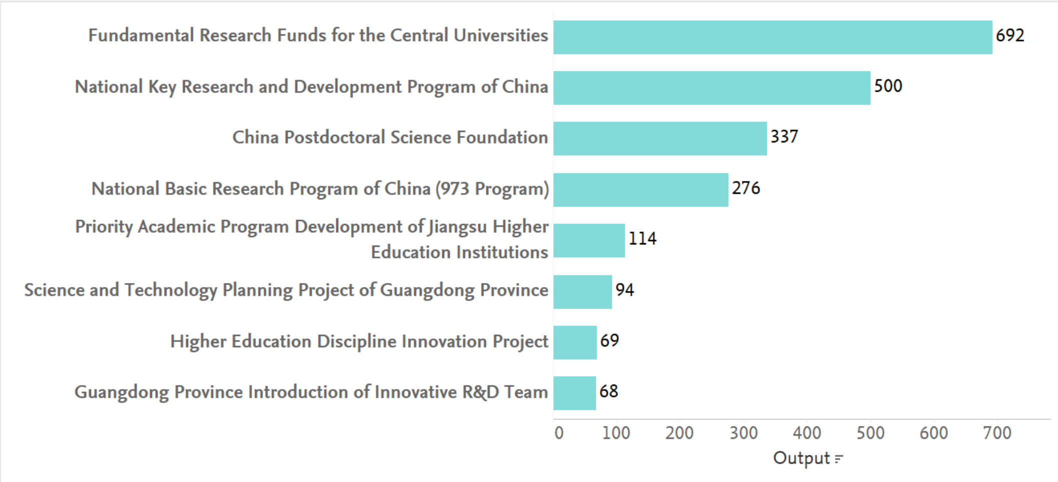

Figure 2.1.3.3 Top 8 grant programs by publication output (>60 funded publications) in the field of AIE, 2012–2021.

Hong Kong University of Science and Technology Partnership

Research collaboration is an important form of scientific achievement. Ideas from other researchers could lead to more significant research results. The search for potential collaborators has also been highlighted as an important issue in the strategic management of science and technology. Understanding an institution's current research partners brings insights into its method of collaboration and research results, which can help in scouting potential partners.

In this subsection, the report analyzes the Hong Kong University of Science and Technology (HKUST); the institution with the highest scholarly output in the field of AIE in the last two decades. The analysis investigates international and national collaborators of HKUST and the results of their collaborative work in the field of AIE from 2012 to 2021.

Analysis of the collaborators of HKUST shows that:

HKUST and South China University of Technology (SCUT) have the closest relationship, and the two institutions are each other's most important national collaborators. Compared to collaborations with other institutions, the partnership between HKUST and SCUT resulted in the highest volume of publications. Their collaborative publications also have a higher scientific impact than work from each individual institution, serving as allies to each other.

Of all of HKUST's research collaborators, the collaborative papers jointly published with Agency for Science, Technology and Research (A*STAR), Singapore have the highest scholarly impact, indicating that the two institutions have higher scholarly impact when collaborating.

I. International partnership

As shown in Figure 2.2.1.1, HKUST's top 10 international collaborators in research publications are mainly from Australia, France, the United Kingdom, Singapore, and Sweden. The National University of Singapore (NUS) has the highest number of international collaborations with HKUST (at 98 publications), followed by A*STAR, Singapore with 71 publications. HKUST's collaborations with the two institutions also have a higher scholarly impact, with FWCIs of 4.9 and 5.1, respectively. Their scholarly impact is the highest among all institutional collaborations.

In terms of HKUST's percentage of international collaborations (the number of collaboratively published articles between an institution and HKUST, out of all of AIE articles produced by the institution), Loughborough University from the UK has the highest percentage of collaborations with HKUST; out of seven AIE publications, four were co-published with HKUST. Flinders University and Karolinska Institute also had a relatively high percentage of collaborative publications with HKUST. Fifty percent of their AIE-related publications were in collaboration with HKUST.

Besides NUS and A*STAR, Durham University (DU) also has a relatively high scholarly impact in terms of collaborative publications, with an FWCI of 4.7, based on four collaborative articles. The FWCIs of other institutions are between 1.4 and 3.3. The international collaborators of HKUST show that HKUST plays an extraordinary role in promoting the international collaboration in the AIE field.

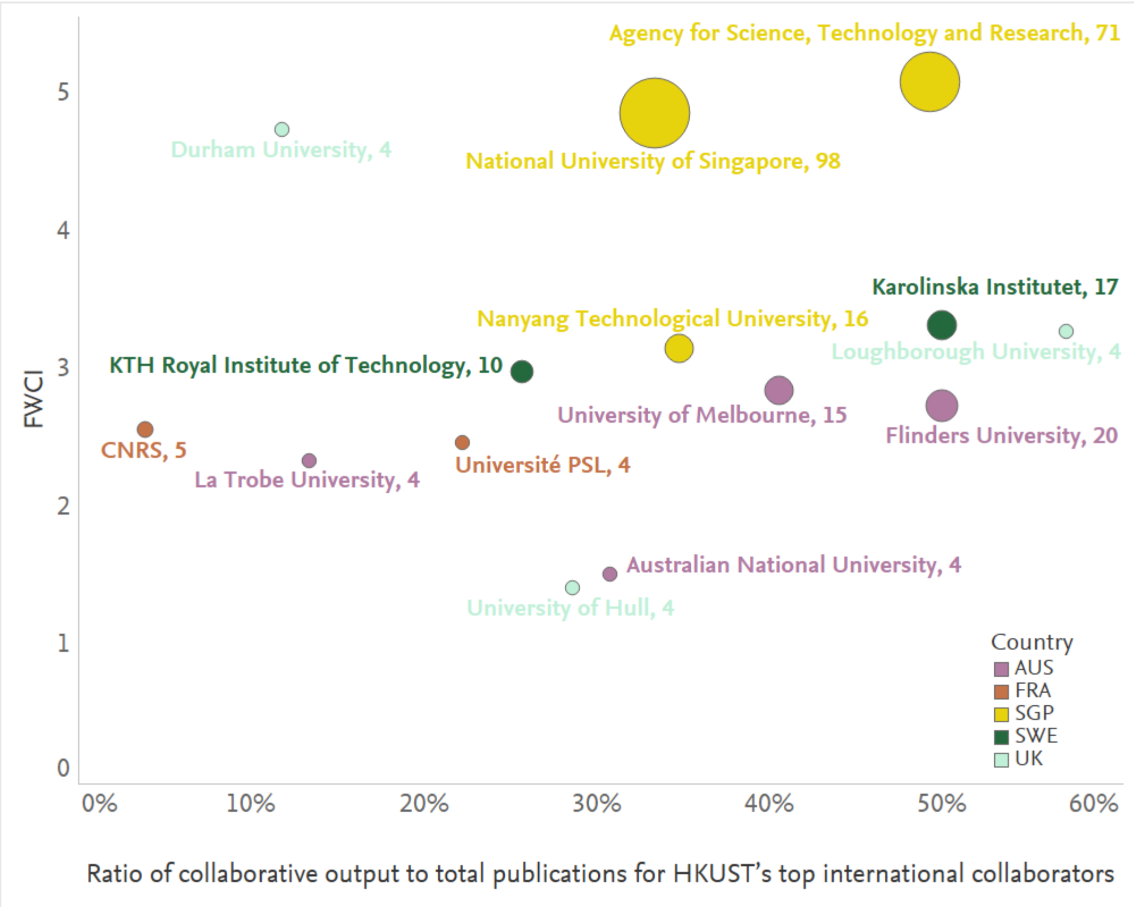

Figure 2.2.1.1 Top international collaborators of HKUST by collaborative publication output and scholarly impact (FWCI) in the field of AIE, 2012–2021. (Country code: AUS-Australia, FRA-France, SGP-Singapore, UK-United Kingdom, SWE-Sweden)

II. National partnership

The top 10 national partners of HKUST from 2012 to 2021 are shown in Figure 2.2.2.1. SCUT has the highest number of national collaborations with HKUST, with 796 publications in AIE research. It also has the highest percentage of collaborative publications, with 76.1% of its AIE articles published in collaboration with HKUST. The FWCI of collaborative publications between HKUST and SCUT reached 3.3, higher than the FWCI of all AIE publications from HKUST (3.2) and SCUT (2.9), respectively. This number shows that the two institutions are allies in the field. Zhejiang University and Shenzhen University are also major national partners of HKUST in this area, with 157 and 106 collaborative AIE publications, respectively.

In terms of the scholarly impact of national collaborations, the partnership between Jilin University and HKUST resulted in the highest FWCI of 4.6. The FWCI of HKUST's collaborative work between Shenzhen University, Chinese Academy of Sciences, Huazhong University of Science and Technology, Zhejiang University, Beijing University of Chemical Technology, SCUT, and Southern University of Science and Technology, is between 3.1 and 3.6.

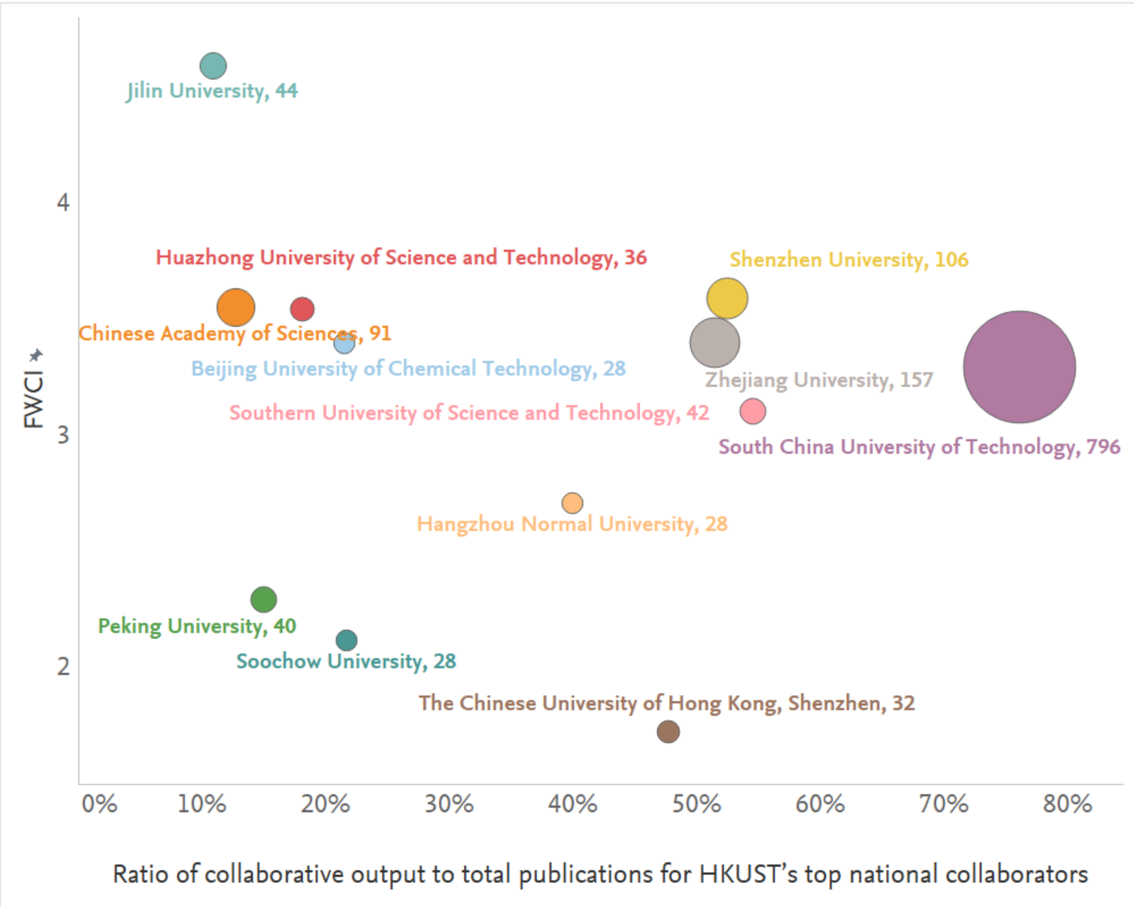

Figure 2.2.2.1 The top national partners of HKUST by collaborative publication output and impact in the field of AIE, 2012–2021.

South China University of Technology Partnership

In this subsection, South China University of Technology (SCUT), an institution with high scholarly output in the field of AIE over the past two decades, is selected as a target institution for analysis. The analysis dives into international and national collaborators of SCUT and the results of SCUT's collaborative work in the field of AIE from 2012 to 2021.

Analysis of the collaborators of SCUT shows that:

SCUT and the Hong Kong University of Science and Technology (HKUST) have the closest relationship, and the two institutions are each other's most important national collaborators. Compared to collaborations with other institutions, the partnership between HKUST and SCUT resulted in the highest volume of collaborative publications. Their collaborative publications also have a higher scientific impact than work from each individual institution; they thus serve as allies to each other.

Of all of SCUT's research partners, the institutions with the highest collaborative scholarly impact are the Agency for Science, Technology and Research (A*STAR) from Singapore and Flinders University from Australia.

I. International partnership

As shown in Figure 2.3.1.1, SCUT's top 10 international collaborators in research are mainly from Australia, Canada, France, the United Kingdom, Singapore, and Sweden from 2012 to 2021. The National University of Singapore (NUS) has the highest number of international collaborations with SCUT, with 77 collaborative publications. Their scholarly impact is the second highest among the institutions, with an FWCI of 4.8. Following that is A*STAR from Singapore, with 47 publications with SCUT, which has the highest scholarly impact with A*STAR at an FWCI of 5.3.

In terms of SCUT's percentage of international collaborations (the number of collaboratively published articles between an institution and SCUT, out of all of AIE articles produced by the institution), Loughborough University from the UK has the highest percentage of collaborative publications with SCUT. Out of seven AIE publications, four were co-published with SCUT. Looking at the numbers, Loughborough University works closely with both HKUST and SCUT in AIE research. The University of British Columbia and Karolinska Institute also have a relatively high percentage of international collaborations, with 57.1% and 44.1% of their AIE-related publications produced in collaboration with SCUT, respectively.

From the perspective of the scholarly impact of collaborative publications, besides NUS and A*STAR, Flinders University has a relatively high FWCI of 5.3. The FWCI of other institutions is between 1.4 and 4.8. It should be pointed out that, in addition to the relatively large number of international collaborations with some universities, the number of articles published by SCUT in collaboration with other universities is small (some less than 10), so the FWCI here only serves as a reference and cannot fully represent the actual level of scholarly impact of the collaboration between these universities and SCUT.

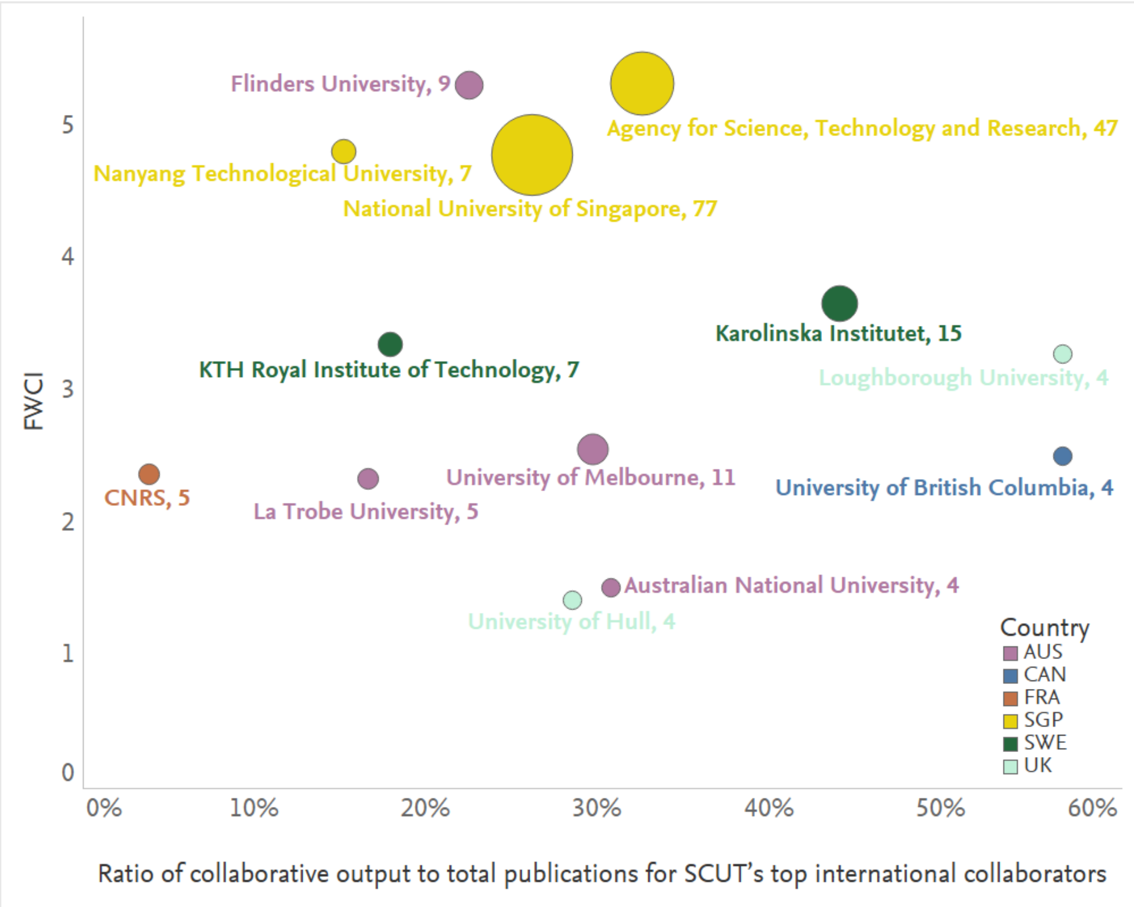

Figure 2.3.1.1 The top international partners of SCUT by collaborative publication output and impact in the field of AIE, 2012–2021.

II. National partnership

The top 10 national collaborators of SCUT by publication count from 2012 to 2021 are shown in Figure 2.3.2.1. SCUT and HKUST have the highest number of national collaborations with each other, at 796 publications, in the field of AIE research. The co-publications accounted for 73.0% of all of HKUST's publications in this area. The FWCI of collaborative publications between HKUST and SCUT reached 3.3, higher than the FWCI of all AIE publications from HKUST (3.2) and SCUT (2.9), respectively. This indicates that the collaboration between the two is mutually reinforcing and that the two institutions are allies in the field. Zhejiang University and Chinese Academy of Sciences (CAS) are also major national partners of SCUT in this area, collaborating on 101 and 77 AIE-related publications, respectively.

In terms of the scholarly impact of national collaborations, the partnership between Shenzhen University and SCUT resulted in the highest FWCI of 4.1. The FWCI of SCUT's co-publications between Jilin University, CAS, Southern University of Science and Technology, Huazhong University of Science and Technology, HKUST, and Zhejiang University lands between 3.2 and 3.6; other university partners have relatively lower FWCIs, ranging from 1.5 to 2.6.

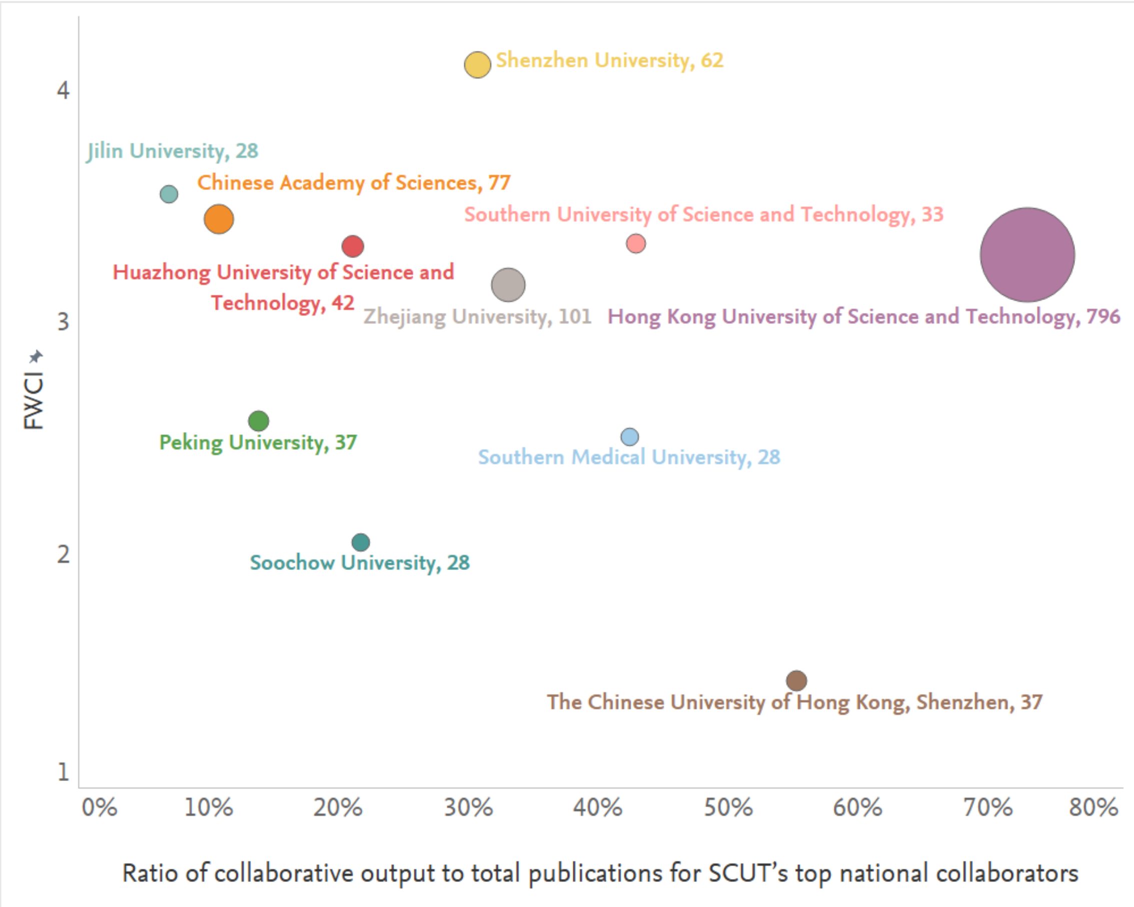

Figure 2.3.2.1 The top national partners of SCUT by collaborative publication output and impact in the field of AIE, 2012–2021.

Chapter 3

Interdisciplinarity and topics of prominence in AIE research

Key Data

Chemistry, Materials Science, Chemical Engineering

The three subject areas in the AIE field with the most publications (2012–2021)

Pharmacology, toxicology and pharmacy, environmental science, energy, and medicine

Emerging subject areas in the AIE field (2012–2021)

China

The country that publishes the broadest array of subjects in the AIE field (2012–2021)

Yangtze River Delta Region

The domestic region with the most diversified research directions in the AIE field (2017–2021)

Tetraphenylethylene; Luminescence; Bioimaging

The most prominent research direction by output in the AIE field (2012–2021)

OLED; Delayed Fluorescence; Electroluminescence

The research direction with the fastest growing publication output in the AIE field (2012–2021)

Phototherapy; Photodynamic Therapy; Photosensitizer

The research area with the highest scholarly impact (FWCI= 3.7) among the top 10 research topics, by output, in the AIE field (2017–2021)

Carbon Dots; TADF; CPL[23]

The research fields that have the most extensive knowledge exchange with the AIE field (2012–2021)

[23] TADF is thermally activated delayed fluorescence; CPL is circularly polarized luminescence.

Subject area distribution of AIE research

Since AIE was first proposed in 2001, it has changed the way people think about the aggregation of chromophores. Basic research in AIE has significantly contributed to the continuous innovation and rapid development of chemistry, materials science, and chemical engineering. As AIE research and applications continue to advance the design and development of new solid-state light-emitting materials, the field has expanded to multiple research areas. Analysis of subject areas within the AIE field can provide a macroscopic view of current AIE basic research and applications around the world. Exploring the diverse disciplines in AIE research among benchmarked countries/regions can provide insights and pave the way for future development.

This subsection uses Scopus' All Science Journal Classification[24] (ASJC), to categorize worldwide AIE publications from the past decade into different subject areas.

Analysis of subject area distribution within AIE research shows that:

Global AIE articles are published in three tiers of subject areas. Chemistry, materials science, and chemical engineering are Tier 1 subject areas with the most AIE articles published globally and are subjects where AIE research originated from. Physics and astronomy, biochemistry, genetics and molecular biology, and engineering are Tier 2 subject areas by AIE publication output, representing important branches of AIE research. Tier 3 subject areas include pharmacology, toxicology and pharmacy, environmental science, energy, and medicine. Although they have a lower share of the total number of AIE publications, the number of publications in these areas has been increasing and they are emerging subject areas for AIE research. The expansion of global AIE research beyond the original research areas indicates that the field is transitioning to an innovation-intensive period.

I. Subject areas of global AIE research

According to the ASJC subject classifications of AIE articles published worldwide from 2012 to 2021, AIE-related publications are widely distributed among 23 of the 27 ASJC subject areas. Figure 3.1.1.1 illustrates the top 10 AIE areas by number of publications. As shown in the figure, the distribution of global AIE articles is categorized into three tiers. Of the three subject areas-chemistry, materials

[24] The ASJC subject classification is defined at the journal level, and it is used by Elsevier experts to classify journals into 27 subject area classifications and 334 subcategories based on the purpose, scope, and content of the journal articles. The subject classification used in this report is the ASCJ 27 subject area classifications, and a list of the 27 subject area classifications categories is detailed in Appendix VII.

science, and chemical engineering, that have the most AIE publications- chemistry has the largest, with 6,050 publications, and accounting for 71% of all global AIE publications. Materials science and chemical engineering have 4,160 and 2,845 publications, which account for 49% and 34% of the global AIE output in their respective area, respectively. These areas are also where AIE research originated, showing that, in the past 10 years, researchers have contributed significantly to the original research areas by establishing and refining AIE theories. Physics and astronomy, biochemistry, genetics and molecular biology, and engineering are Tier 2 subject areas, with approximately 1,000 to 2,000 AIE articles published, and accounting for 14% to 18% of global publications. These subject areas represent the extension of fundamental theories and knowledge from the original subjects of AIE research. They are important branches of research for the advancement of AIE research.

In recent years, as AIE research has advanced toward new material applications, the field has expanded to diverse subject areas. Tier 3 subject areas, including pharmacology, toxicology and pharmacy, environmental science, energy, and medicine, are emerging as novel areas of AIE research. These subject areas are expected to play an increasingly important role in the future development and application of new AIE materials.

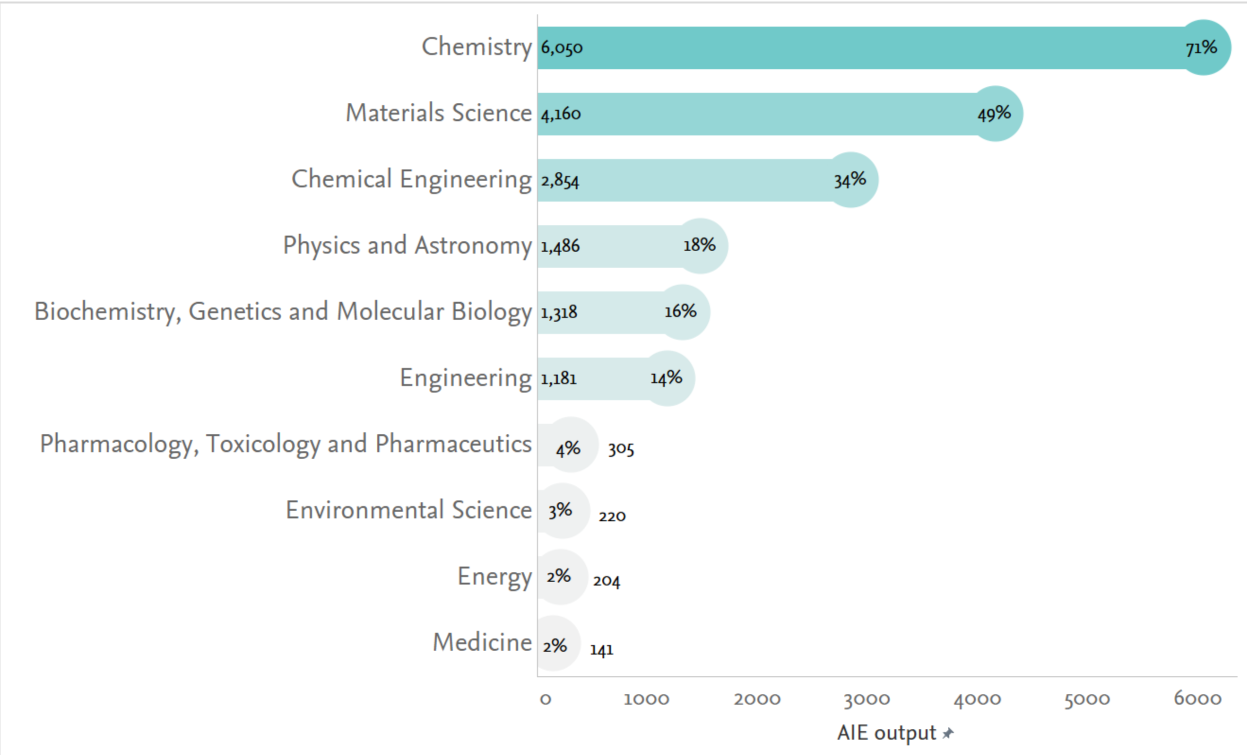

Figure 3.1.1.1 Top 10 ASJC subject areas by AIE scholarly output and the share of publications in the subject area, 2012–2021.

II. Subject area distribution of AIE research in benchmarked countries

In this section, we shift our focus from the world to individual countries. By analyzing the subject distribution of AIE publications in benchmark countries, the report presents major subject areas in each country as shown in Figure 3.1.2.1. China, a leader in AIE research, has the broadest distribution, with 14 subject areas having at least 15 AIE publications, far ahead of other benchmarked countries. This indicates that China has the advantage of subject diversity in AIE research. Matching China's top subject areas, other countries mainly publish AIE research in the areas of chemistry, materials science, and chemical engineering. In addition, these countries also have a notable volume of AIE publications in physics and astronomy, biochemistry, genetics and molecular biology, and engineering. Overall, the global AIE research landscape is evolving from its initial phase to an innovation-intensive period with no clear differences in the distribution of subject areas between countries. Notably, AIE research in India has seen a small surge of publications in energy and environmental sciences. This could become a unique research focus and direction that differentiates India's AIE research from that of other countries.

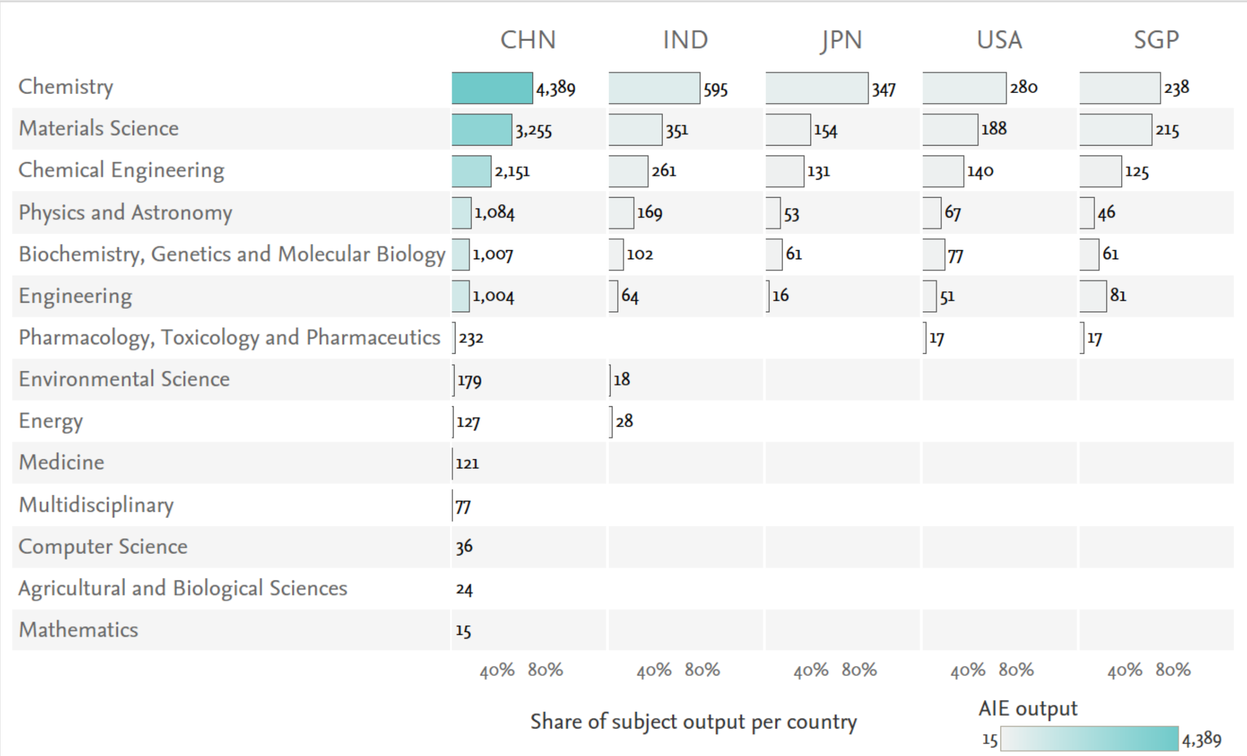

Figure 3.1.2.1 ASJC subject area distribution of AIE publication output for the top five countries with AIE output, 2012–2021. Subject areas with 15 or more publications are shown; the number indicates the publication output in that subject by a country; the length of the bar indicates publication output in that subject as a share of the total output for a country. Country code: CHN-China, IND-India, JPN-Japan, SGP-Singapore, USA-United States)

Extended areas of AIE research

As a new research area grows, it draws on knowledge that is readily available in related research areas, while at the same time contributing its own innovative discoveries. In this section of the report, we select nine research areas that are closely related to AIE research and explore the interaction between them from the perspective of knowledge flow. Specifically, we aim to show how knowledge flows into AIE research from the nine research areas and how, in turn, AIE research promotes the development of these nine areas. The analysis may further help inform the future development of AIE research.

The following nine research areas that are closely related to AIE research were selected: thermally activated delayed fluorescence (TADF), room temperature phosphorescence (RTP), circularly polarized luminescence (CPL), mechanoluminescence, carbon dots, bioprobe, luminescent solar concentrator, excited state intramolecular proton transfer (ESIPT), and twisted intramolecular charge transfer (TICT). We retrieved all publications in these nine research areas[25].

The knowledge exchange between AIE research and the nine research areas was measured by counting the number of articles cited by, or citing, AIE publications in the last decade.

Analysis on the extended research areas of AIE shows that:

The citation counts show that AIE research and the nine research areas have various degrees of knowledge exchange. Three research areas—carbon dots, TADF, and CPL—have the most extensive knowledge exchange with the field of AIE. Of the nine research areas, AIE research cited the most publications from TADF and carbon dots, both of which contributed substantial scientific knowledge to the field of AIE. Parallelly, the field of AIE also contributed scientific knowledge to the nine research areas, especially to the areas of TADF and CPL; 50% of publications in these two research areas cited AIE research as a reference.

I. The knowledge exchange between AIE and the nine research areas

Knowledge exchange between AIE and the nine research areas is examined from the perspective of knowledge inflow and outflow. The inflow of knowledge from the nine research areas to the field of AIE is measured by the number of publications from the nine areas that are cited as references by AIE research, from which we infer that they help advance the development of AIE research. In

[25] See Appendix I for the field definitions and how the article publications were obtained.

contrast, the outflow of knowledge, from the field of AIE to the nine research areas, is measured based on the number of AIE publications that were cited as references by the nine areas, from which we infer that AIE research helps advance scientific development in these research areas.

Figure 3.2.1.1 illustrates the inflow and outflow of knowledge between the field of AIE and the nine research areas from 2012 to 2021. As shown in the figure, carbon dots and TADF had the most frequent knowledge exchange with the field of AIE, by the number of publications cited by or citing AIE research. In the last decade, 1,298 of the 9,096 carbon dots publications were cited as references by AIE research publications. Among the nine areas, carbon dots had the most publications cited by AIE research, followed by TADF with 1,216 publications. In terms of the number of publications citing AIE research, TADF ranks first, with 1,673 of the 3,253 TADF publications citing AIE articles published in the last decade, followed closely by carbon dots with 1,561 publications.

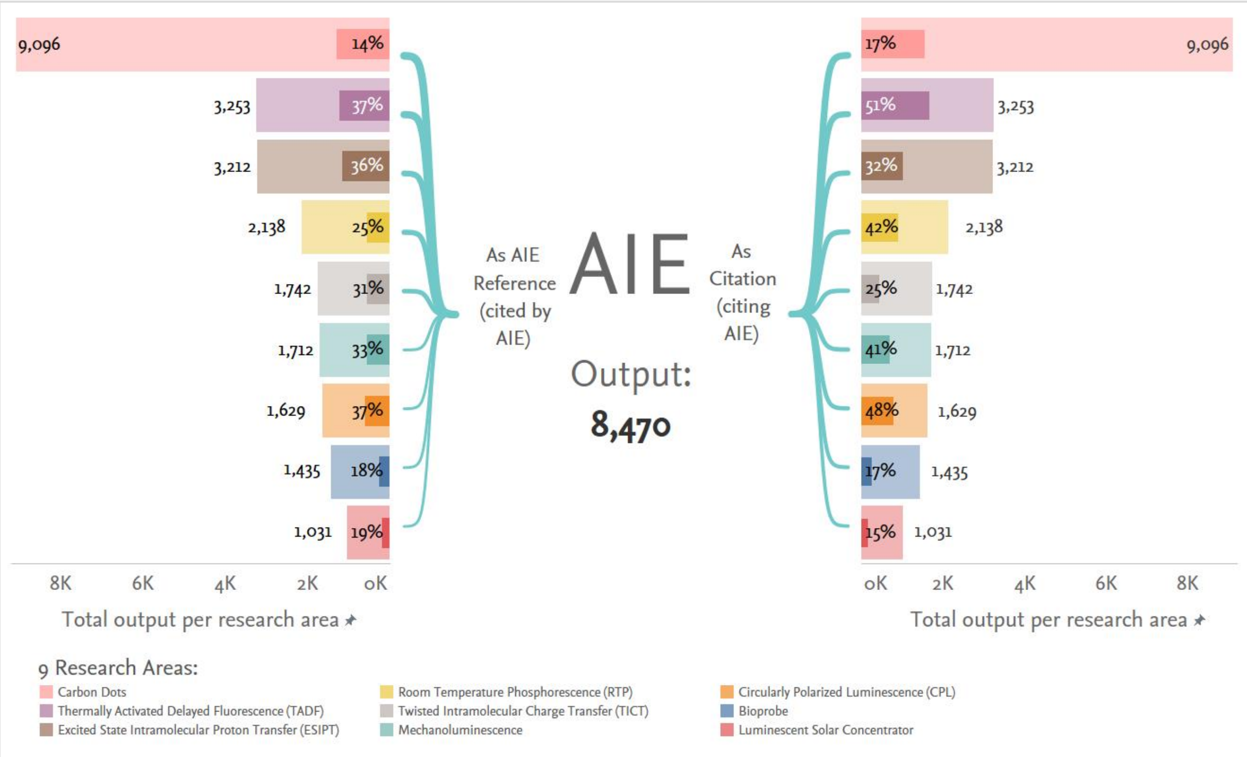

Figure 3.2.1.1 Number and share of publications in the nine research areas that cite or are cited by AIE research, 2012–2021. Bars of lighter color on both sides of the panel indicate the scholarly output for each research areas; bars of deeper color on the left indicate the output of the research areas cited by AIE research, and bars of deeper color on the right indicate the output citing AIE research.

TADF and CPL have the highest percentage of publications citing or cited by AIE research. This indicates that these two research fields have the most extensive knowledge exchange and significant interaction with the AIE research field. In particular, approximately 50% of the articles in these two fields cited AIE research published in the past 10 years. This number indicates that AIE research plays a significant role in supporting and promoting scientific development in these two research areas.

A comparison of AIE-related citation pattern in the nine research areas showed that the percentage of publications citing AIE research was greater or close to the percentage of publications that were cited by AIE research. This suggests that the outflow of knowledge, from AIE research to the nine areas, was greater than the inflow of knowledge, from the areas to AIE research. It indicates that AIE research contributes significantly to the development of the nine research areas.

Topics of prominence in AIE research

This section presents "hot" topics in AIE research, providing a detailed picture of research directions in the field of AIE. This topic analysis uses a method that clusters publications with common research interests together. For this purpose, Elsevier uses machine learning to categorize publications from the entire Scopus database into more than 96,000 research topics, delineating these topics through citation patterns, so that research that appears in the same citation network is clustered together in the same topic. The advantage of taking a citation-based approach to identify research topics is that one need not rely on identifying all the relevant keywords to define a research area. Publications under the same topic relate[26] to each other's content strongly.

On this basis, the analysis also incorporates an indicator for research activity/research topic prominence. The value can reflect researchers' interest in a research topic, as well as a topic's popularity and trends[27]. Through the clustering algorithm, AIE articles are categorized into different research topics based on the relationship between citing and cited publications. Analyzing the distribution of AIE publications in popular research topics not only reveals cutting-edge areas that involve AIE research, but also helps researchers identify new research directions that could be worth pursuing. In addition, extracting highly relevant key phrases through a content analysis of articles classified under different topics can provide detailed insights into productive research directions. Further comparison of the subjects within AIE research among countries/regions can provide details about the similarities and differences of the subjects in various locations and offer information for strategic planning and research advancement.

This subsection selects the world's top 10% prominent research topics with high prominence for analysis. It shows the distribution of AIE articles on popular topics published in the past 5 or 10 years by national regions, benchmarked countries, and global trends. By comparing AIE research content within popular research topics, the subsection showcases the direction of research in the field.

Analysis of topics of prominence shows that:

Over the past 10 years, AIE research publication output in several "hot" research topics has grown, indicating the active publication of AIE research that intersects with many cutting-edge research

[26] See Appendix V for details of how the research topics were clustered.

[27] Research topic prominence can reflect researchers' interest in the research topic, as well as the topic's popularity and trends; prominence generally shows a positive correlation with factors such as research funding and grants, among others. Identifying significant research topics can lead researchers and program managers to obtain more funding. See Appendix V for algorithms for the indicators.

areas globally. In addition, AIE research is associated with topics that are among the most popular in the world. This indicates that AIE research has substantial overlap with prominent global research. The distribution of AIE articles among research topics of prominence in the benchmarked countries shows that China has the most diverse distribution, with the highest publication output on several topics. In contrast, AIE research in other countries still mainly focuses on similar research topics and research directions, indicating that AIE research in these countries has not yet developed unique characteristics. However, in China's key regions, AIE research does involve distinctive topics, which is worth noting.

I. AIE research in global topics by prominence

i. Key phrase cloud map for top 10 topics by prominence

This section presents the focuses of AIE research using a word cloud generated from publication key phrases that were drawn from the top 10 research topics of prominence (those with the highest prominence scores).

Combining text mining and natural language processing, SciVal uses Elsevier Fingerprint Engine to extract key phrases[28] from titles, abstracts, and author keywords to showcase the main research focus of a collection of publications. SciVal is based on the Inverse Document Frequency (IDF) algorithm, which assigns a normalized relevance score to each phrase in the collection. This algorithm can reduce the weight of frequently occurring phrases in the collection and increase the weight of less frequent ones, so that the key phrases can be balanced and comprehensively reflect the focus of research in the collection. The word cloud is generated by ranking the top 50 key phrases, from highest to lowest relevance.

As shown in Figure 3.3.1.1, the most relevant key phrases in the field of AIE from 2012 to 2021 under the top 10 topics of prominence are “aggregation” and “induced emission.” Other key phrases with high relevance include AIE-related applications, such as organic light-emitting diodes (OLED), photothermal therapy, fluorescent dye, bioimaging, and explosive detection; AIE-related molecular structures such as tetraphenylethene, and Schiff base; and AIE-related mechanisms such as dark state and excited states. In addition, the key phrases in the figure are all shown in green, indicating that the number of AIE articles associated with these key phrases has been on the rise for the last 10 years. These AIE-related research focus topics are continuously growing and expanding.

[28] https://service.elsevier.com/app/answers/detail/a_id/27763/supporthub/scival/kw/Fingerprint/

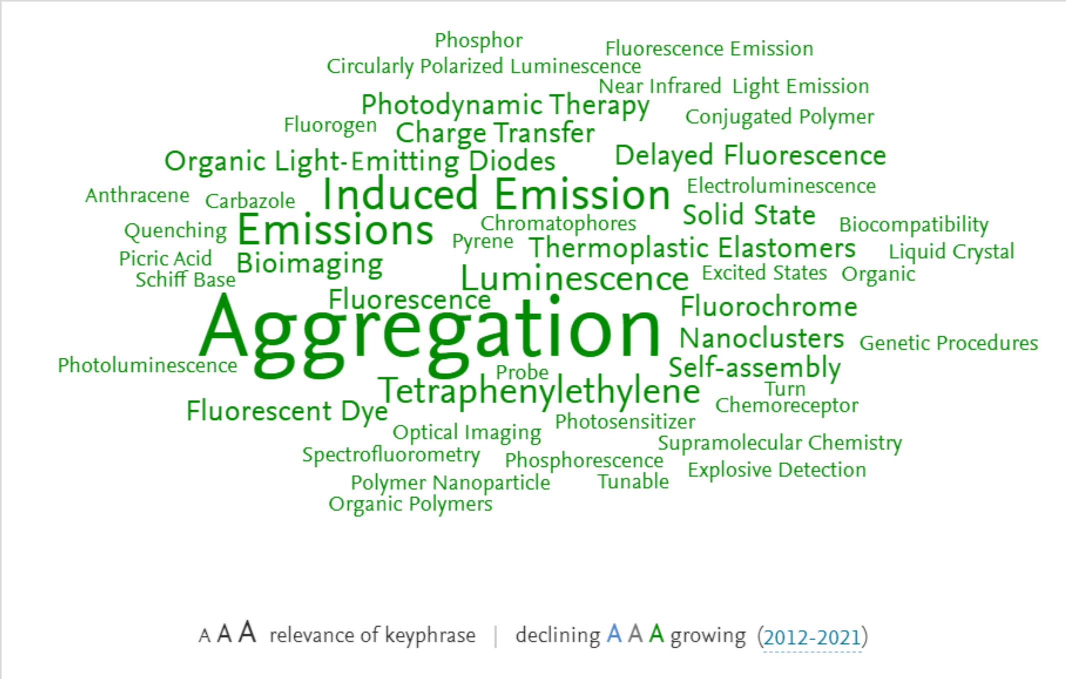

Figure 3.3.1.1 Top 50 key phrases for top 10 topics by prominence, based on global publications, 2012–2021. Key phrase size represents relevancy; green represents the increasing number of relevant publications in recent years; blue represents the decreasing number of relevant publications in recent years.

ii. Topics of prominence with the highest AIE publication output during different time periods

This section focuses on the top 10 topics of prominence in AIE research by the number of publications, covering two time periods: 2012–2016 and 2017–2021. It shows the changes in the publication volume and scholarly impact (FWCI) of AIE-related research under different topics.

Figure 3.3.1.2 shows the three most relevant key phrases under each topic of prominence[29] to showcase the research focus of AIE-related publications on the respective topics.

From the perspective of publication output, global AIE articles are positioned mainly under the topic of prominence ID T. 2829 "Tetraphenylethylene; Luminescence; Bioimaging"[30]. From 2012 to 2021, the total number of publications on this topic was 4,220, accounting for 73% of all publications within this topic. AIE research can be regarded a major contributor to this topic.

[29] For details about key phrase extraction from AIE article collection under a topic of prominence, and the definition of key phrase relevance, please refer to the explanation of key phrases on page 75 of the report.

[30] The naming of research topics is generated by SciVal in a data-driven manner based on phrases (e.g., important concepts or keywords) extracted from the titles, abstracts, and author keywords of articles attributed to the topic. Specifically, the three phrases that make up the name of a research topic are a combination of the characteristics of high frequency and uniqueness, that is, they are not only high frequency phrases for articles on the topic, but are also sufficiently unique to distinguish them from other research topics. In addition, the naming of research topics distinguishes between phrases from titles and abstracts, and the algorithm gives more weight to phrases extracted from titles, making research topic names better aligned with the titles of articles on the topic. https://service.elsevier.com/app/answers/detail/a_id/35058 /supporthub /scival/

Prominence	Topic Id	Most Relevant Keyphrase	Topic Output 2012-2016	Topic Output 2017-2021	Changes	FWCI 2012-2016	FWCI 2017-2021	Changes
99.86	2829	*Tetraphenylethylene; Luminescence; Bioimaging	1,292	2,928	↑	2.5	1.6	
99.85	158	*Organic Light-Emitting Diodes; Delayed Fluorescence; Electroluminescence	19	254	↑	4.0	2.1	
99.81	1445	*Nanoclusters; Gold Nanoclusters; Luminescence	31	205	↑	3.9	1.8	
99.24	12558	Pillar(5)arene; Supramolecular Polymer; Supramolecular Chemistry	22	116	↑	2.9	2.2	
99.39	897	*Fluorescent Dye; Chemoreceptor; Cupric Ion	23	95	↑	1.6	1.6	
98.92	28763	Circularly Polarized Luminescence; Circular Polarization; Chiral	18	73	↑	2.5	2.7	↑
99.96	5315	Tetraphenylethylene; Micro Porosity; Coordination Polymer	16	72	↑	3.1	3.6	↑
99.95	1195	*Carbon Quantum Dot; Graphene Quantum Dot; Fluorescence	5	70	↑	2.7	2.2	
96.54	8906	*Picric Acid; Explosive Detection; Explosives	22	69	↑	2.7	1.3	
99.97	3466	Photothermotherapy; Photodynamic Therapy; Photosensitizer	0	67	↑	0.0	3.7	↑
97.91	6738	*Fluorescent Dye; Zinc Ion; Chemoreceptor	17	66	↑	3.9	1.4	
98.26	902	Organogel; Gelation; Gel	40	59	↑	1.9	1.1	
98.94	6037	*4,4-difluoro-4-bora-3a,4a-diaza-s-indacene; Boron; Solid State	30	55	↑	2.4	1.4	
97.31	1328	Phosphorescence; Iridium Complex; Iridium	17	39	↑	1.5	1.0	

Figure 3.3.1.2 Top 10 topics of prominence by ID, key phrases, and scholarly output, globally, 2012–2016 and 2017–2021. The maximum score for the research topic of prominence is 100, and the higher the score, the higher the degree that the AIE-related research topic is active globally. For example, a research topic prominence of 99.9 indicates that the research topic is active globally to a greater extent than 99.9% of all topics. *Indicates that the top three keywords of prominence in the subject set originally contained the AIE subject terms "aggregation" or "induced emission" but were removed due to the repetitive nature of the content.

As shown in the figure above, excluding the key phrase "Aggregation Induced Emission," the three most relevant key phrases in the collection of 4,220 AIE publications under the topic ID T.2829 are "Tetraphenylethylene," "Luminescence," and "Bioimaging." Among these, the most frequent was tetraphenylethylene, a functional group that has been widely used to synthesize various new AIE materials. Moreover, because of the excellent thermal and structural stability of tetraphenylethylene derivatives, AIE luminescent materials constructed by tetraphenylethylene have great potential in high-performance OLED devices. Luminescence is an important concept in luminescent materials. Based on transition radiation, luminescence can be divided into two types: fluorescence and phosphorescence materials with diverse structures and properties are commonly used in optoelectronic and biological fields. Given the special properties of fluorescent molecules, fluorescent materials are widely used in emerging disciplines and technologies, such as organic luminescent materials, fluorescent labeling, and fluorescent molecular probes. These are a focus area of AIE research; that is, the exploration of organic luminescence mechanisms. Figure 3.3.1.3 illustrates the key phrase word cloud of 4,420 AIE publications under the popular research topic ID T.2829.

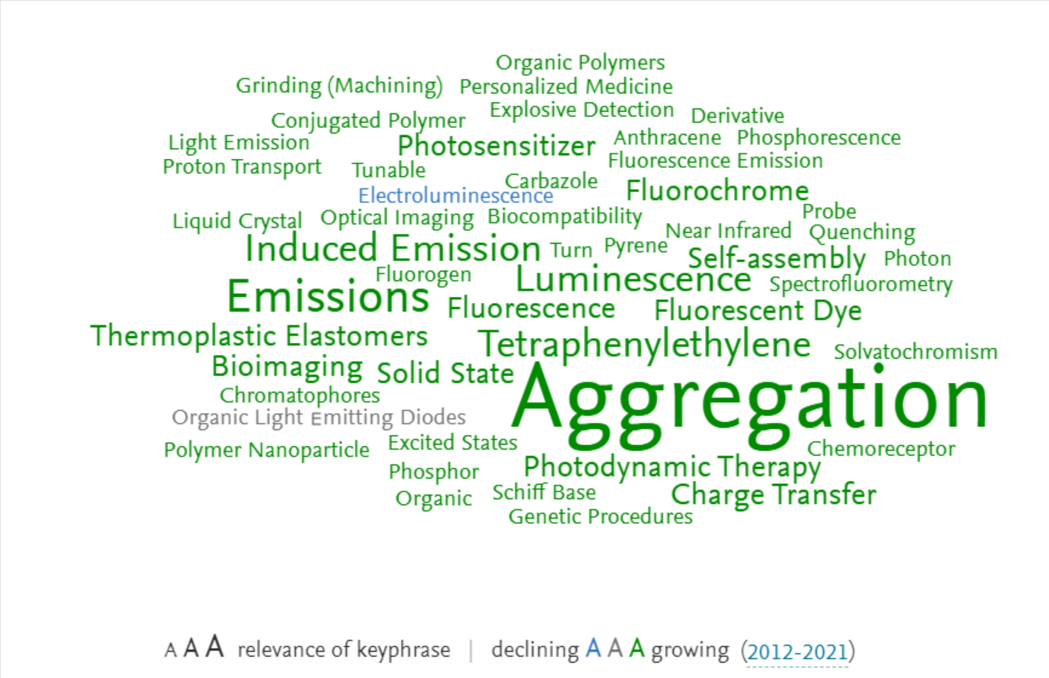

Figure 3.3.1.3 Key phrase word cloud generated from AIE publications under topic of prominence ID T. 2829, 2012–2021. Key phrase size represents relevancy; green represents the increasing number of relevant publications in recent years; blue represents the decreasing number of relevant publications in recent years; grey represents the number of relevant articles that remained stable.

From the perspective of the growing number of AIE-related articles on topics of prominence, Figure 3.3.1.2 shows that topic ID T.158 had the greatest increase in publication volume. The topic was a fast-growing research area characterized by the key phrases "Organic Light-Emitting Diodes," "Delayed Fluorescence," and "Electroluminescence." The number of publications surged from 19, in the period 2012–2016 to 254 in the period 2017–2021, representing a 12.3-fold increase in volume. Compared to inorganic materials, organic materials have important and practical applications in OLEDs, organic transistors, and organic solar cells. The application of AIE materials to organic optoelectronic devices has a great advantage due to their enhanced luminescence performance in the aggregated state. Currently, AIE materials are being increasingly used in high-efficiency OLED devices with different light-emitting colors. AIE light-emitting materials with higher luminous efficiency and stability could lead to breakthroughs in the performance of OLED devices. Showing promising prospects[31], AIE materials in the field of optoelectronics is a research direction that is primed for rapid development and application. Figure 3.3.1.4 shows the key phrase word cloud of 273 AIE articles under the popular research topic ID T.158.

[31] Jou JH, Kumaae S, Agrawal A, Li T H, Sahoo S. Approaches for fabricating high efficiency organic light emitting diodes, J Mater Chem C, 2015, 3:2974-3002

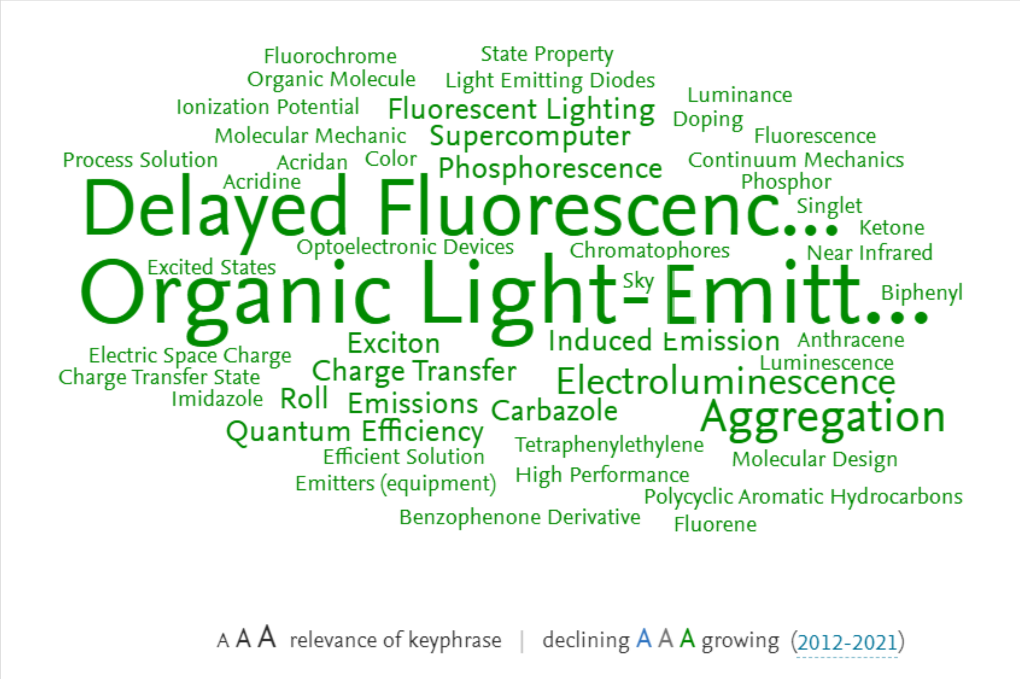

Figure 3.3.1.4 Key phrase word cloud generated from AIE publications under topic of prominence ID T.158[32], 2012–2021. Key phrase size represents relevancy; green represents the increasing number of relevant publications in recent years; blue represents the decreasing number of relevant publications in recent years.

Figure 3.3.1.2 also shows the scholarly impact of publications on one of the world's most prominent research topics, T.3466 "Photothermotherapy; Photodynamic Therapy; Photosensitizer." This topic saw the largest surge in FWCIs in the last five years. It forms an emerging high-impact research direction represented by the key phrases "Photothermotherapy," "Photodynamic Therapy," and "Photosensitizer." The FWCI value of AIE-related publications in this topic is 3.7, which is the highest among the top 10 topics of prominence with the most publications. This topic includes the outstanding scientific achievements of AIE research in cancer diagnosis and treatment, as well as nanomedicine. Specifically, molecules with AIE properties have made breakthroughs in cancer therapy in 2021: they were designed with the ability to recognize and gather in the organelles of cancer cells. Powered by far-infrared light, these AIE molecules can emit strong fluorescence and generate reactive oxygen species, which have cancer-killing properties without damaging normal cells in the body[31]. With more clinical research, AIE research has the potential to revolutionize current cancer treatments. Figure 3.3.1.5 shows the keyword cloud of 67 AIE articles under the topic of prominence ID T.3466.

[32] The full forms of "Delayed Fluorescenc..." and "Organic Light-Emitt..." in the figure are "Delayed Fluorescence" and "Organic Light-Emitting Diodes."

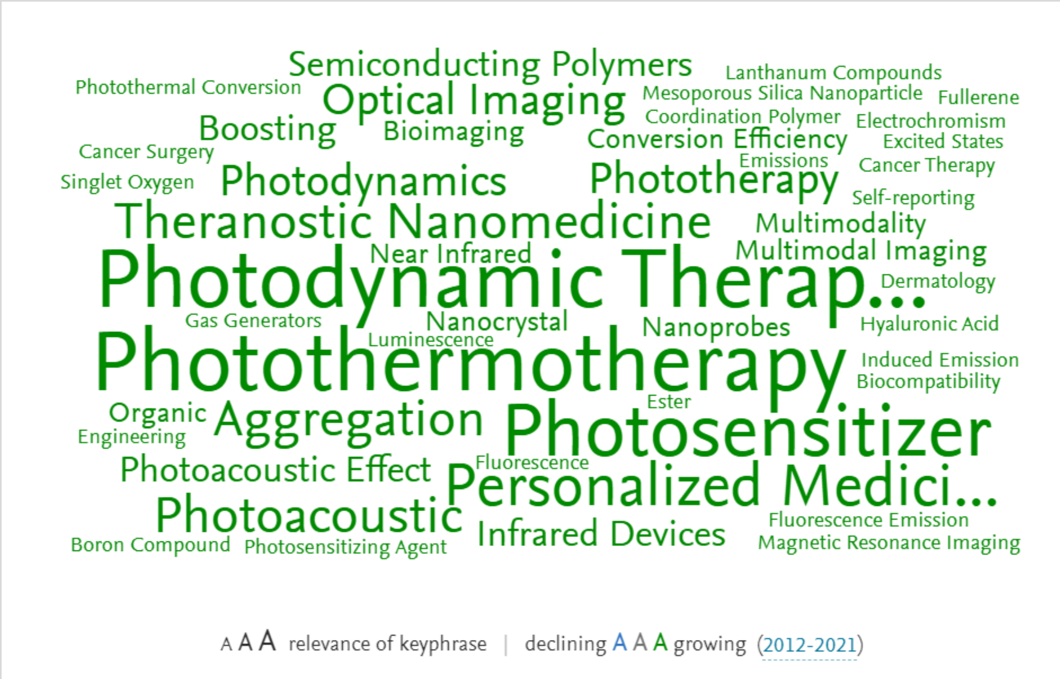

Figure 3.3.1.5 Key phrase word cloud generated from AIE publications under research topic of prominence ID T.3466[33], 2012–2021. Key phrase size represents relevancy; green represents the increasing number of relevant publications in recent years; blue represents the decreasing number of relevant publications in recent years.

Overall, AIE research has seen varying levels of increase in publication output on different topics of prominence in the last decade, indicating that the field is flourishing. Most of the research topics with the highest number of AIE publications also have a prominence score of 99 or higher, meaning that the AIE-related topics are more active than 99% of the research topics globally; further showing that AIE topics are trending and are some of the most interesting areas to researchers.

II. AIE research on topics of prominence in benchmarked countries

In this section, the report presents an overview of AIE research-related topics across benchmarked countries over the past five years to characterize these countries' research direction. It also explores the countries' advantages and scholarly impact. As shown in Figure 3.3.2.1, similar to the global distribution of AIE articles, most of the research in each country is centered around topic T.2829, a research direction represented by the key phrases "Tetraphenylethylene," "Luminescence," and "Bioimaging." Among the countries selected for analysis, Singapore has the highest scholarly impact on this topic, with an FWCI of 3.1; China is the country with the most diverse research direction in AIE, and Chinese AIE articles are widely distributed under several topics of prominence, showing multiple research directions. Among these topics, T.25125 "Optical imaging;

[33] The full forms of "Photodynamic Therap..." and "Personalized Medici..." in the figure are "Photodynamic Therapy" and "Personalize Medicine."

Fluorochrome; Bioimaging" has the highest FWCI value of 5.1. It indicates that China's AIE research has the highest scholarly impact in this research area, and that it is where the strength of China's AIE research lies.

Prominence	Topic Id	Most Relevant Keyphrase	CHN	IND	USA	JPN	SGP
99.86	2829	*Tetraphenylethylene; Luminescence; Bioimaging	2,240	290	109	129	124
99.85	158	*Organic Light-Emitting Diodes; Delayed Fluorescence; Electroluminescence	199				
99.81	1445	*Nanoclusters; Gold Nanoclusters; Luminescence	175				
99.24	12558	Pillar(5)arene; Supramolecular Polymer; Supramolecular Chemistry	113				
99.39	897	*Fluorescent Dye; Chemoreceptor; Cupric Ion	66	18			
99.97	3466	Photothermotherapy; Photodynamic Therapy; Photosensitizer	65				
98.92	28763	Circularly Polarized Luminescence; Circular Polarization; Chiral	63				
99.77	12937	Coordination Polymer; Luminescence; Metalorganic Frameworks	57				
99.95	1195	*Carbon Quantum Dot; Graphene Quantum Dot; Fluorescence	55				
99.96	5315	Tetraphenylethylene; Micro Porosity; Coordination Polymer	55				
99.52	3044	*Tetraphenylethylene; Self-assembly; Supramolecular Chemistry	48		24		
99.07	25125	*Optical Imaging; Fluorochrome; Bioimaging	46				
96.54	8906	*Picric Acid; Explosive Detection; Explosives	46	16			
97.91	6738	*Fluorescent Dye; Zinc Ion; Chemoreceptor	35	23			

FWCI 1.0 – 5.1

Figure 3.3.2.1 The top topics of prominence by ID, key phrases, and scholarly output for the top five countries by AIE output, 2017–2021. Topics shown in the chart: top topics by output for China and topics with no less than 15 publications for other countries. The maximum score of research topic prominence is 100, and the higher the score, the higher the degree of activity in the AIE-related research topic globally. For example, a research topic prominence of 99.9 indicates that the research topic is active globally to a greater extent than 99.9% of the topics. *Indicates that the top three keywords of prominence in the subject set originally contained the AIE subject terms "aggregation" or "induced emission" but were removed due to the repetitive nature of the content.

III. AIE research in domestic regions under topics of prominence

In this section, the report provides a cross-sectional comparison of the prominent research topics related to AIE research in the four regions of China (Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, and Hong Kong SAR of China) over the past five years. The comparison shows the landscape of AIE research in different regions for the topics T.2829 "Tetraphenylethylene; Luminescence; Bioimaging" and T.158 "Organic Light-Emitting Diodes; Delayed Fluorescence; Electroluminescence," which are also the top topics in global AIE publication distribution. In addition, AIE publications for the topic T.25125 "Optical Imaging; Fluorochrome; Bioimaging" in the Pearl River Delta (PRD) region, Yangtze River Delta (YRD) region, and Hong Kong, China, show high scholarly impact. Their FWCIs were 5.3, 5.3, and 6.9, respectively. This research direction is a unique strength of China.

The Beijing-Tianjin-Hebei (BTH) region, led by the Chinese Academy of Sciences, has the highest number of publications for research topic T.2829 "Tetraphenylethylene; Luminescence; Bioimaging," with 689 articles. In addition, compared to other areas, AIE research in the BTH region shows a unique advantage for topic ID T.5315, the new research direction represented by the key phrases "Tetraphenylethylene," "Micro Porosity," and "Coordination Polymer." This research direction not only reached a notable scale (16 articles) but also achieved a high scholarly impact value (FWCI=3.0).

Prominence	Topic Id	Most Relevant Keyphrase	Beijing-Tianjin-Hebei	Pearl River Delta	Yangtze River Delta	HKG
99.86	2829	*Tetraphenylethylene; Luminescence; Bioimaging	689	610	578	438
99.85	158	*Organic Light-Emitting Diodes; Delayed Fluorescence; Electroluminescence	38	92	56	56
99.81	1445	*Nanoclusters; Gold Nanoclusters; Luminescence	30	22	48	
98.92	28763	Circularly Polarized Luminescence; Circular Polarization; Chiral	24	16	27	
99.97	3466	Photothermotherapy; Photodynamic Therapy; Photosensitizer	22	30		19
99.96	5315	Tetraphenylethylene; Micro Porosity; Coordination Polymer	16			
99.24	12558	Pillar(5)arene; Supramolecular Polymer; Supramolecular Chemistry	16		38	
99.07	25125	*Optical Imaging; Fluorochrome; Bioimaging		23	23	16
95.13	8274	Alkyne; Click; Explosive Detection		17		18
99.77	12937	Coordination Polymer; Luminescence; Metalorganic Frameworks			25	
99.48	2961	*Electrochemiluminescence; Conjugated Polymer; Nanoclusters			18	
99.52	3044	*Tetraphenylethylene; Self-assembly; Supramolecular Chemistry			28	
99.35	55149	*Phosphorescence; Room Temperature; Organic			29	

FWCI 1.4 – 6.9

Figure 3.3.3.1 Top topics of prominence by ID, key phrases, and scholarly output for four domestic regions in China, 2017–2021. Topics with 15 or more publications are shown. The maximum score of research topic prominence is 100, and the higher the score, the higher degree the AIE-related research topic is active globally. For example, a research topic prominence of 99.9 indicates that the research topic is active globally to a greater extent than 99.9% of topics. *Indicates that the top three keywords of prominence in the subject set originally contained the AIE subject terms "aggregation" or "induced emission" but were removed due to the repetitive nature of the content.

The YRD region, led by Zhejiang University, has the most diverse set of topics of prominence related to AIE research, with 10 topics each with more than 15 AIE publications. Among them, the unique research directions in the region are T.129357 "Coordination Polymer; Luminescence; Metalorganic Frameworks," T.2961 "Electrochemiluminescence; Conjugated Polymer; Nanoclusters," T.3044 "Tetraphenylethylene; Self-assembly; Supramolecular Chemistry," and T.55149 "Phosphorescence; Room Temperature; Organic." These four research directions performed well, with 18 to 29 publications.

The PRD region, led by South China University of Technology, had 92 publications in the research direction T.158 represented by the key phrases "Organic Light-Emitting Diodes," "Delayed Fluorescence," and "Electroluminescence;" significantly more publications than from the other three regions. This points to the fact that AIE research-related research directions from Hong Kong, China, generally have a high scholarly impact.

Chapter 4

Industrial application and translation of AIE research

Key Data

78%

Percentage of articles with academic–corporate collaboration that were published in the last 4 years

National University of Singapore

Academic institution with the highest scholarly impact (FWCI=4.9) in AIE academic–corporate collaboration (2012–2021)

Samsung Group

Corporation with the highest scholarly impact (FWCI=5.1) in AIE academic–corporate collaboration (2012–2021)

3%

Percentage of AIE publications that have been cited at least once by patents from the top patent offices, which is three times the average patent citation rate (1%) of global publications (2012–2021)

1,616

Number of patent families related to AIE research, 92% of which were invented in China (2012–2021)

2015

The year when AIE patent applications entered a period of rapid growth

China

Country with the highest AIE Patent Asset Index (PAI=1,387) (2012–2021)

United States

Country with the highest AIE Competitive Impact (CI=3.2) (2012–2021)

84%

Percentage of AIE patents owned by universities and research institutes (2012–2021)

HKUST

Patent owner with the largest AIE patent families (123) (2012–2021)

Academic–corporate collaboration in AIE research

The technological advancement and translation of research outcomes can improve society and benefit a nation's economic development and productivity. The key to research translation is academic–corporate collaboration. Academic–corporate collaboration refers to research partnerships between industry and academia. "Industry" includes corporate and for-profit institutions; "academia" refers to universities and other research institutions. Academic–corporate collaboration is important for transforming innovation from academia to industrial applications.

AIE research has been a revolutionary breakthrough in the field of organic luminescence and has strong potential for industrial applications. An analysis of the performance of academic–corporate collaboration in AIE research can help inform the progress of this transformation to industry, as well as provide an outlook on its future prospects.

This subsection of the analysis focuses on the publication output and scholarly impact of global academic–corporate collaborations in the field of AIE from 2012 to 2021. It also identifies leading institutions and corporations in the field.

Analysis of academic–corporate collaboration within the AIE field shows that:

Academic–corporate collaborative research activities in the field of AIE are still at the initial stages of development. Although overall publication output is relatively small, it has grown rapidly in the past four years. Limited by the relatively small volume of scholarly output, the scholarly impact of collaborative publications is also slightly lower than average. However, collaborative publications between certain universities and corporations showed high scholarly impact. In AIE research, the analysis shows that there is room for growth in academic–corporate collaboration.

I. The performance of academic–corporate collaboration

The scholarly impact and level of research collaboration between academic institutions and corporations can be quantified by FWCI and the collaborative publication output in AIE research. As shown in Figure 4.1.1.1, 42 academic–corporate collaborative publications were published from 2012 to 2021. The number represents only 0.5% of all publications in the field. Because of the limited number of academic-corporate publications, the scholarly impact of collaborative publications (FWCI=1.4) is lower than the AIE field's overall average (FWCI=1.9).

Notably, 78% of the articles produced through academic–corporate collaboration were published in the last four years, indicating that this type of collaboration is recent and has begun to develop rapidly. To a certain extent, the progress of AIE research is consistent with the developmental trajectory of emerging research fields. In the past 10 years, the leading theories in the field of AIE have been established and continuously refined. The development of new technologies and applications has been carried out as the field enters an innovation-intensive period. AIE researchers in academia have started to work with industrial researchers to transform their discoveries into industrial applications.

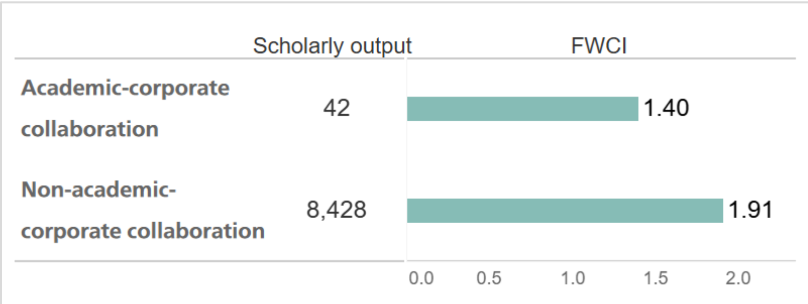

Figure 4.1.1.1 Output and scholarly impact (FWCI) of academic–corporate and non-academic–corporate collaborative publications, globally, 2012–2021.

II. Leading research institutions and corporations in academic–corporate collaboration

This section explores the leading research institutions and corporations in AIE-related academic–corporate collaborative research. The report identifies the key players in the field from the perspective of the output and scholarly impact (FWCI) of collaborative publications.

Most of the research institutions that are active in AIE academic–corporate collaboration are from China. As shown in Figure 4.1.2.1, the number of publications by leading research institutions involved in academic–corporate collaboration are relatively close to each other. Specific institutions stand out for the scholarly impact of their collaborative publications. Among these institutions, the National University of Singapore has the highest FWCI of 4.9, followed by Kyushu University (FWCI=2.6) and Beijing University of Chemical Technology (FWCI=2.0). Of note, given the small number of academic–corporate collaborative publications, the resulting FWCI value does not fully reflect the actual research impact of the institution in terms of academic–corporate collaboration, and this indicator is only a point of reference.

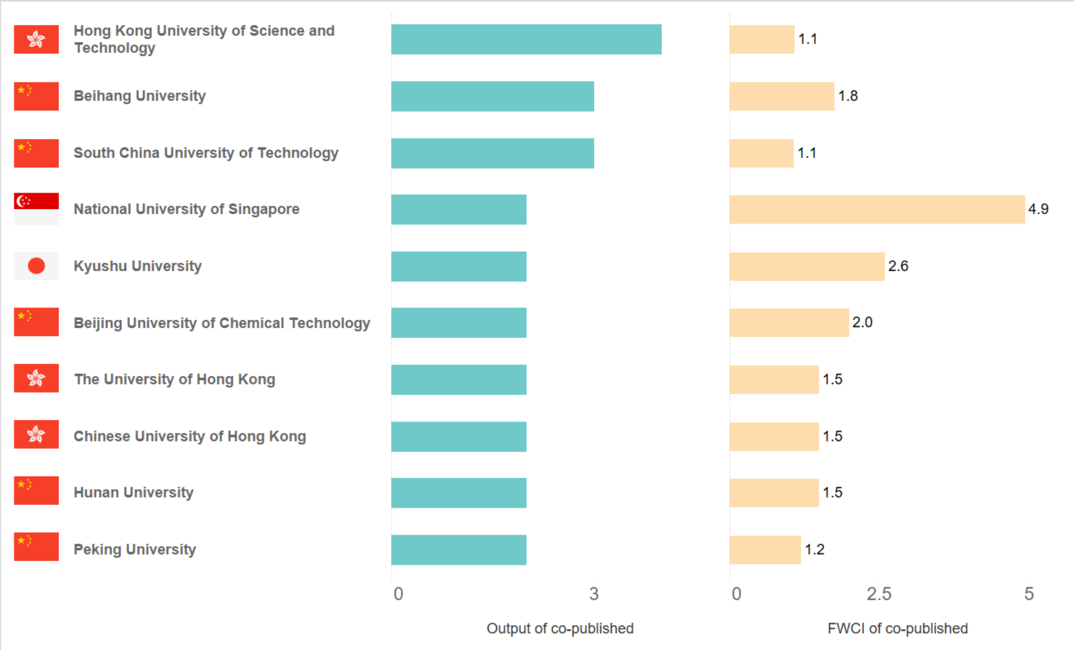

Figure 4.1.2.1 Academic–corporate collaborative publication output and FWCIs for the top research institutions in AIE research, globally, 2012–2021.

In contrast to research institutions, which are concentrated in China, corporations with active AIE academic–corporate collaboration are associated with multiple countries. As shown in Figure 4.1.2.2, Sinopec (China Petro-Chemical Corporation) is the most active company by number of academic–corporate collaborative publications, with four publications. Samsung and Singapore Public Healthcare Cluster Holdings (MOH Holdings) lead in scholarly impact of collaborative publications with FWCIs of 5.1 and 4.9, respectively.

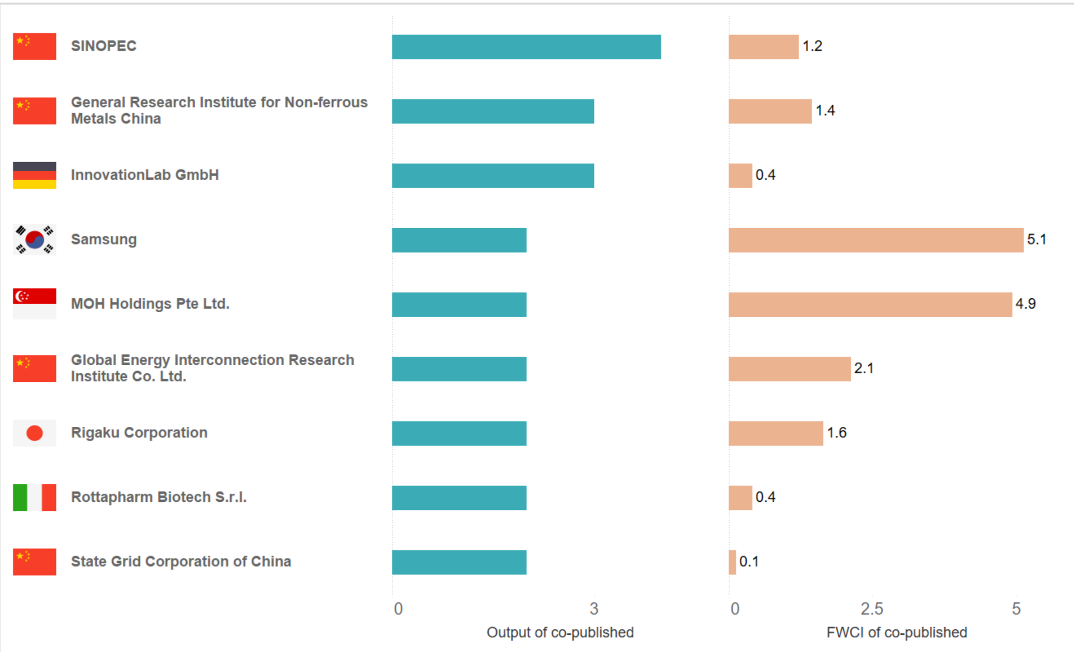

Figure 4.1.2.2 Academic–corporate collaboration publication output and FWCI of the top corporates in the field of AIE globally, 2012–2021

AIE research and patent citations

The analysis of academic–corporate collaborative publications in the previous section focuses on AIE research outcomes through cross-sectoral collaboration. This subsection explores the effectiveness and impact of AIE research outcomes in industrial applications through cross-sectoral citations. It specifically focuses on the use of AIE research in patent development to further identify areas of interest for translating AIE research technology to fit industry needs.

More specifically, this subsection analyzes patent citations of AIE articles from 2012 to 2021. It does so by tracing the citation relationship between 8,470 publications from the Scopus database and patent records from the five largest international patent offices[34]. Since the patent citation in this section is limited to patents from the five major international patent offices (World Patent Office, US Patent Office, European Patent Office, UK Patent Office and Japan Patent Office), the tracking of "publication-patent" citation relationships do not cover patent data from the Chinese Patent Office. Two indicators are used in the analysis: 1) the number of patents citing AIE publications, which measures AIE research's impact on industrial technology, and 2) the number of AIE publications cited by patents, which shows the extent to which AIE research is applied to product development and patent creation, which can reflect potential for industrial application.

Analysis on patent citations of AIE research shows that:

AIE research articles are cited by patents from industries such as OLED, pharmaceuticals, biotechnology, and chemicals, indicating that AIE research has had a positive impact on technological innovation in these areas. Research institutions in China are the primary contributors of AIE articles cited by patents, showing they are the major institutions that are shepherding AIE knowledge to industry.

I. Patents citing AIE publications

From 2012 to 2021, a total of 266 patents from the top five international patent offices cited AIE publications. To further understand the source of these patents, Figure 4.2.1.1 shows the top 10 patent owners with patents that cite the most AIE publications. The Hong Kong University of Science and Technology (HKUST) is the largest patent owner, with 34 patents citing AIE research. National University of Singapore (NUS) ranks second, with 11 patents citing AIE research. Considering that these two universities are also the most active in AIE research, this indicates that

[34] The top five global patent databases include the World Intellectual Property Organization, the United States Patent and Trademark Office, the United States Patent and Trademark Office, the UK Intellectual Property Office and the Japan Patent Office.

HKUST and NUS are also actively applying AIE research to the development of their own patented technology. In addition to higher education, owners of patents that cite AIE research also come from industries closely related to AIE research applications. These corporations include Novaled Gmbh, a German organic electronics company; Quantapore, Inc., a US pharmaceutical company; Tokyo Ohka Kogyo Co., Ltd, a Japanese chemical manufacturer; and Adocia, a French biotech company. This shows that AIE research has great application potential in these industries.

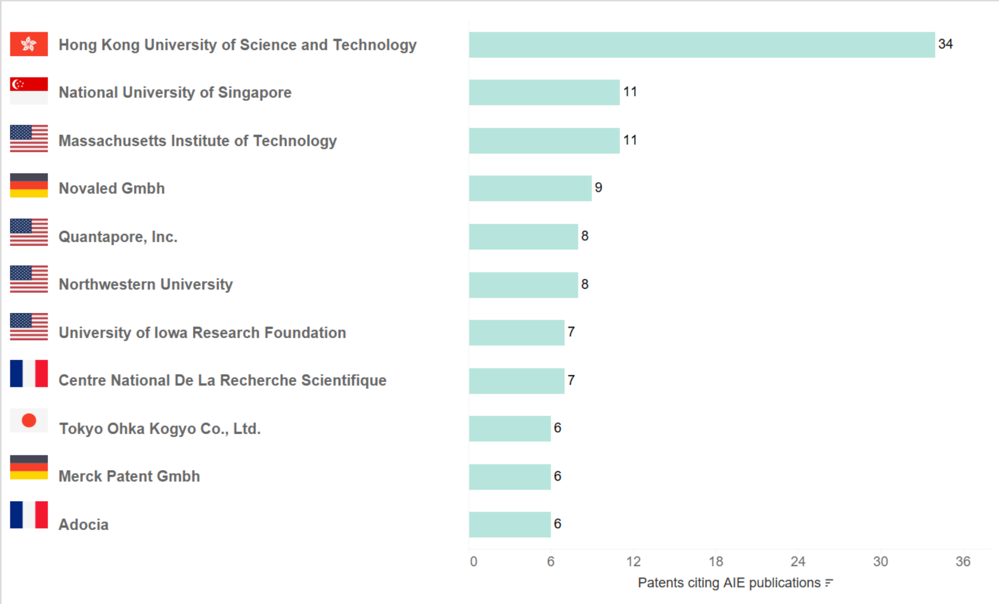

Figure 4.2.1.1 Top patent owners by number of patents citing AIE publications, 2012–2021.

II. AIE publications cited by patents

Over the past 10 years, a total of 257 AIE-related publications have been cited by patents from the five international patent offices. This number accounts for 3% of the total AIE publication output, which is three times the average patent citation rate (1%) for global publications during the same period. However, the current patent citation rate has certain statistical limitations because the database used to track the publication-patent citation relationship does not include the Chinese patent office. Given that China is a leading country in AIE research and development, the actual patent citation rate should be higher.

From available data, AIE publications cited by patents mainly originate from academic institutions in China and Singapore. As shown in Figure 4.2.2.1, HKUST and South China University of Technology have 101 and 82 AIE publications cited by patents, respectively. Both universities are leading research institutions exporting AIE-related knowledge to industry.

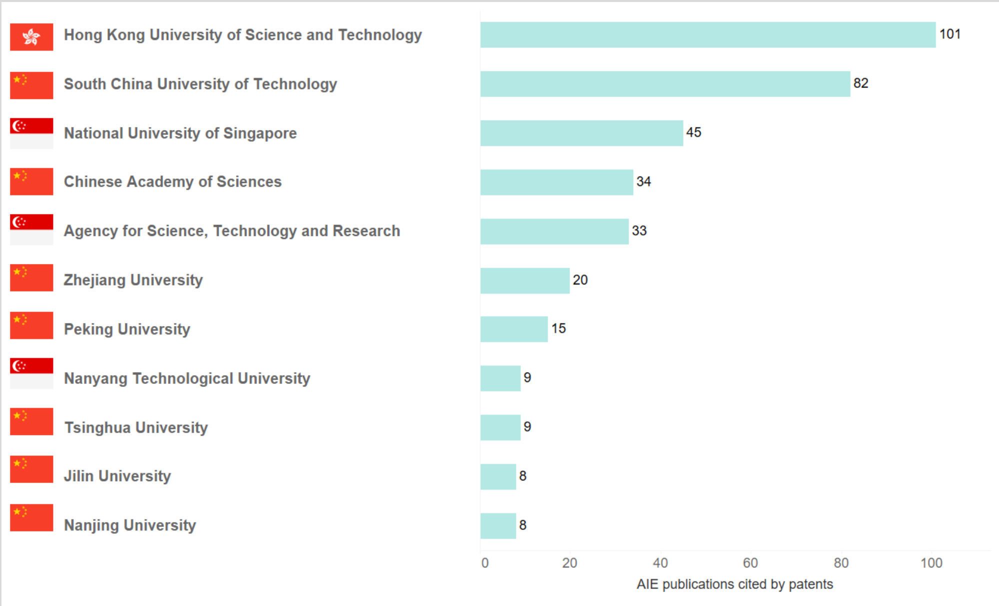

Figure 4.2.2.1 Top institutions by number of AIE publications cited by patents, 2012–2021.

Analysis of patents in AIE research

The first two sections of this chapter dive into the impact of AIE research on technological innovation and development in industry through academic–corporate collaboration and patent citation relationships. That analysis was based on research outcomes in the form of publications in the field of AIE. This subsection focuses on another innovation index in AIE research patents and inventions. The report aims to present trends in the development of AIE materials and technologies in industrial applications, revealing the unique features of AIE patents, to provide information for the industrialization of AIE patents.

The patents analyzed are from documents issued by patent offices in 115 countries/regions included in the LexisNexis® PatentSight® platform. Based on the patent search[35] results, the report shows trends in patent application, benchmarked countries' patent numbers and impact, and important patent owners.

Analysis of patents within the AIE field shows that:

In 2015, the number of AIE patent applications entered a period of rapid growth, with China leading in AIE materials and technological innovation. Current AIE patents are mainly in the fields of chemistry, information technology, medicine and health, and electronics. Most AIE patent owners are universities and research institutions (84%), while corporate owners account for a relatively small proportion (14%). This may be because AIE materials and technology are still at an early stage of commercialization. In recent years, the Chinese government has been introducing policies and regulations to accelerate translation of research to industry, which will speed up AIE research technology transfer between universities and corporations. There is great potential for the commercialization and industrialization of AIE patents.

I. Global trends in patent application

To fully reflect the historical trend of AIE's patent applications and better reflect the development of patent technology, the number of patents included in this report is based on a patent family. In other words, the same patent filed and granted under the Chinese patent office and foreign patent offices are combined into one patent family; by merging patents (the report prioritizes the selection of Chinese patents as representations of the patent family), the statistical analysis can focus on the same technology.

[35] For details about the search of AIE patents, please refer to Appendix IV.

Figure 4.3.1.1 shows the trend in the number of AIE-related patent applications (including inactive patents) since 2001. The first AIE-related patent applications appeared in 2004 but the number of applications did not grow much in the following years. It wasn't until 2015 that the number of related patent applications started pick up significantly, increasing from less than 50 applications before 2015 to 405 in 2019. When considered together with the growth trend in publications, these data show that, beginning in 2013, AIE publication entered a period of exponential growth. Active scientific research and the resulting technology transfer mean that the development of AIE-related patents has entered a stage of rapid growth as well.

In terms of Technology Clusters[36], the distribution of AIE patents has remained relatively stable since 2015. The top five technology clusters, by number of AIE patents, are: olefin polymerization (13.6%), chromatography (12.5%), polymer composition (7.5%), electrochemical sensor (7.5%), and staining (6.6%).

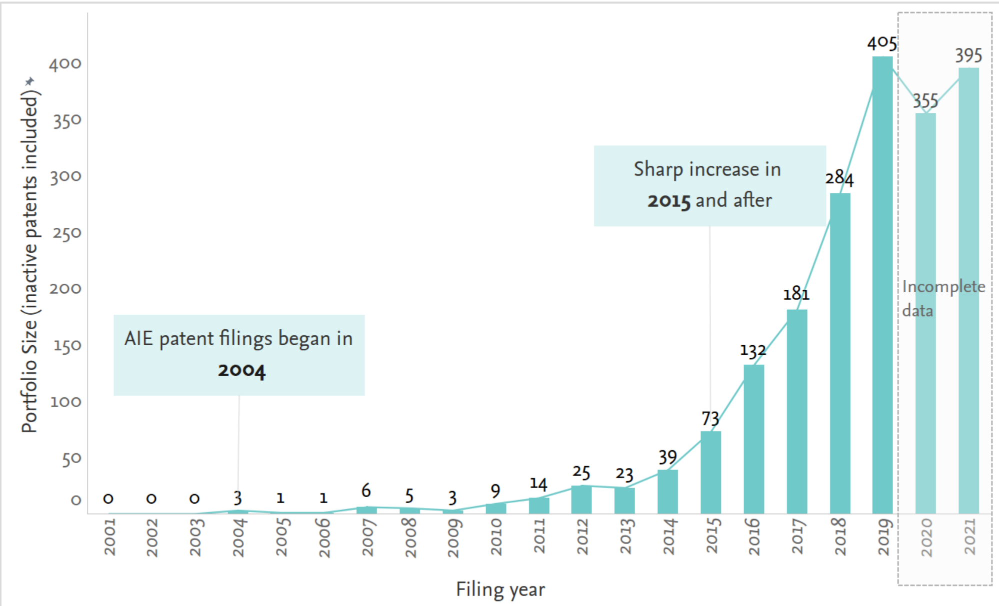

Figure 4.3.1.1 Annual trend of AIE patent filings, including inactive patents, globally, 2001–2021. There is an average two-year delay between patent filing and publication. The data in the figure are an estimate and are likely to be significantly smaller than the actual data. Patent search date: 2022/7/21, data source: LexisNexis® PatentSight®

II. Current scale of active patent families

AIE-related active patent families globally have grown rapidly over the past 10 years. The number of active patent families has increased from 44 in 2012 to 1,616 today, a 36-fold increase in 10 years. This indicates that the global AIE research has made great progress in patent technology development.

[36] LexisNexis® PatentSight® uses artificial intelligence to define relevant fields, express technology content using natural language, and categorize patent families into specific technology categories under the classification concept of "technology clustering."

If the authority of AIE active patent families were based on the country where the inventors of the patent family are located, China would be the country with the largest portfolio, as shown in Figure 4.3.2.1. By the end of 2021, China's accumulated number of AIE-related active patents was 1,488, accounting for 92% of the global total, 33 times as many as the number for the US, which ranks second. The number of active patents shows that China is active in AIE technology development and is the main driver of growth in global AIE patent applications. Although the portfolio size of the US (45), Korea (32), and Japan (27) is much smaller than that of China, the numbers have all grown in varying degrees over the past 10 years, with average annual growth rates ranging from 16% to 30%. Singapore's number of active AIE patent families has remained around 10 in the past five years, behind the US, Japan, and South Korea.

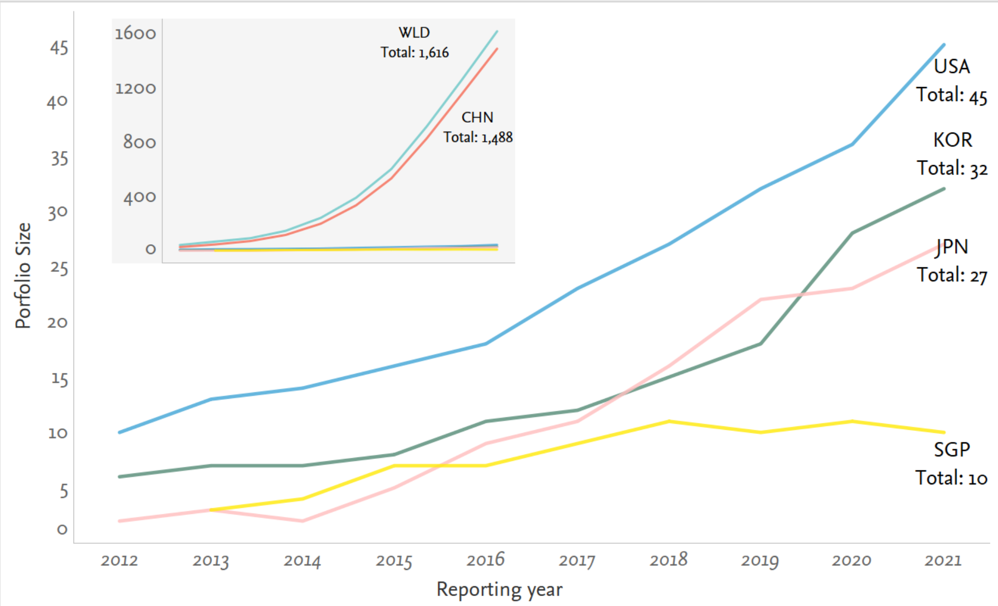

Figure 4.3.2.1 Accumulated number of active AIE patent families, globally and for the top five patent holding countries (2012–2021). There is an average two-year delay between patent filing and publication, so the current number of active patent families is reflected as the accumulated number. Patent search date: 2022/7/21. Data source: LexisNexis® PatentSight® (Country code: CHN-China, JPN-Japan, KOR-Korea, SGP-Singapore, USA-USA, WLD-World)

III. Patent impact

This section analyzes the AIE patent impact of the benchmarked countries. The two indicators used in the analysis are the Patent Asset Index™ (PAI) and the patent Competitive Impact (CI).

PAI is the sum of the CI of all patent families in a portfolio and can be used to measure a portfolio's overall advantages and combined strength. Patent CI is calculated for the patent family level and it is obtained by multiplying the technology relevance (TR) and the market coverage (MC) of a patent family. TR is the technical value based on the number of citations a patent family has received. MC measures the level of patent protection on a global scale, which can represent the market impact of a patent[37].

Figure 4.3.3.1 compares PAI, number of patents, and CI of the top five countries with the largest AIE patent portfolio. As shown in the figure, the PAI (represented by the size of the bubble) reflects a portfolio's combined strength. The horizontal axis shows the portfolio size and the vertical axis shows the average CI value of a patent family in the portfolio. China's PAI (1,387) is well ahead of other countries, mainly due to its large portfolio size (1,488). However, in terms of the average competitiveness of a patent family, China's patent CI value (0.9) is lower than that of the US (CI=3.2), Singapore (CI=3.1), and Japan (CI=2.3). Overall, China leads the world in the number of AIE patents, but there is still room for improvement in the average patent's competitive impact.

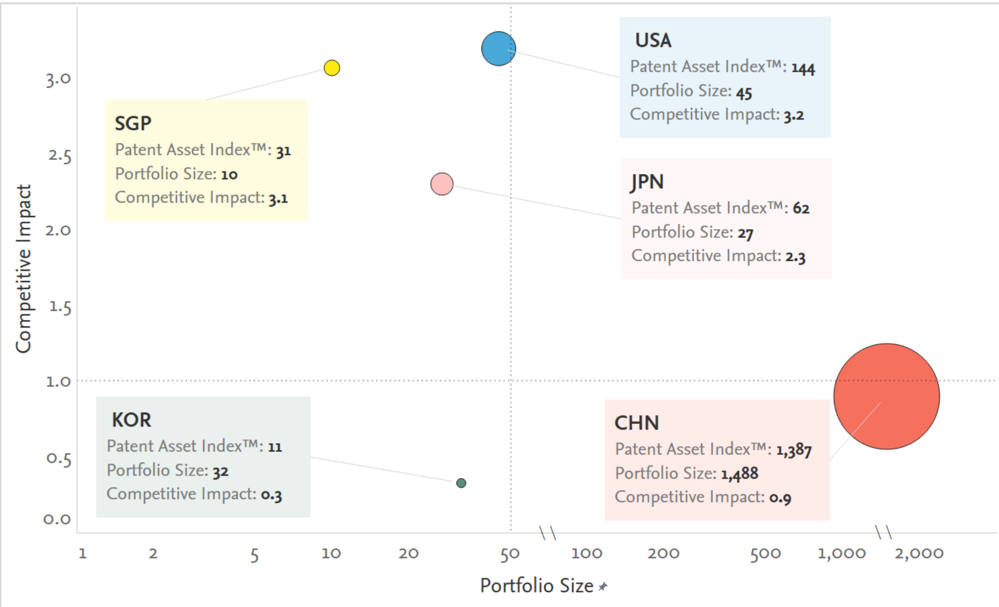

Figure 4.3.3.1 Portfolio size, Competitive Impact (CI), and Patent Asset Index (PAI) of the top five countries by number of AIE patents, as of December 31, 2021. The size of the bubbles indicates the size of the Patent Asset Index (PAI). Patent search date: 2022/7/21, Source: LexisNexis® PatentSight® (Country code: CHN-China, JPN-Japan, KOR-Korea, SGP-Singapore, USA-USA)

To further understand each country's advantages in AIE competitive impact, Figure 4.3.3.2. compares the TR and MC, which are indicators of patent competitiveness. As shown in the figure, the United States' AIE patent competitiveness surpasses that of other countries because of a relatively balanced advantage in TR and MC. China's MC of AIE patents is relatively weak, lagging behind the United States, Japan and Singapore. This is, in part because, although many Chinese AIE patent holders have applied for patent protection in other countries around the world, the vast majority of them focus on local protection. Thus, the average MC value of China's overall patents is limited.

In terms of patent TR, Singapore has the strongest overall performance. Its patent portfolio on the manufacturing and application of AIE fluorescent bio-probes (patent family number:

[37] See Appendix V for a detailed explanation of each indicator.

CN103842472A) has been highly cited, leading to a strong TR. It should be noted that the patent was first jointly applied for by the National University of Singapore and the Hong Kong University of Science and Technology. Further, a lower TR does not mean that China lacks in patents with high impact on technical development. In fact, China leads the world in the absolute number of AIE patents with high citation impact but, based on the large number of patents, the advantage is not well reflected in the percentage rates. As a result, China's average performance of patent TR is less advantageous than that of other countries.

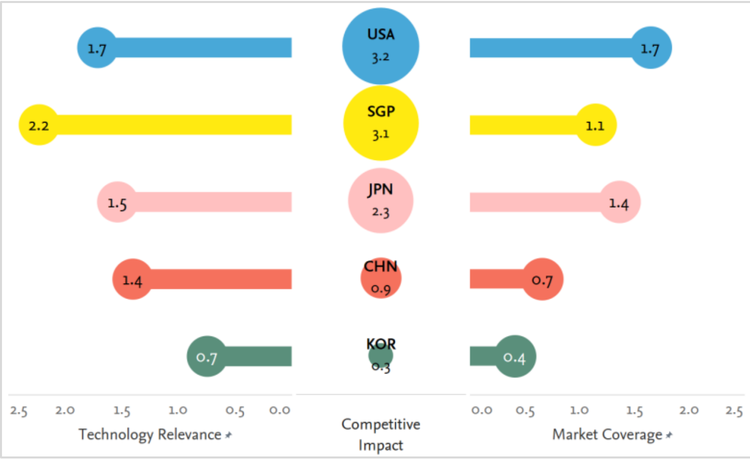

Figure 4.3.3.2 Patent competitive impact (CI) displayed in the dimensions of technology relevance (TR) and market coverage (MC), top five AIE patent-owning countries by portfolio size, as of December 31, 2021, patent search date: 2022/7/21, data source: LexisNexis® PatentSight® (Country code: CHN-China, JPN-Japan, KOR-Korea, SGP-Singapore, USA-USA)

IV. Important Patent Owners

While universities and research institutions own 84% of AIE patents, only 14% are owned by corporations and the remaining 2% are owned by individuals. This indicates that universities and research institutions are the driving force behind the development of patented AIE technologies. In contrast, corporate-led patent technology development is relatively limited. This may also show that AIE materials and technology are emerging fields yet to be commercialized.

In terms of the nationality of identifiable patent owners, the ratio of Chinese to non-Chinese owners is approximately 7:3. From these, non-Chinese patent owners are affiliated with 11 countries, with the largest share of AIE patent owners from the United States (24), followed by Japan and South Korea.

Looking at the number of active AIE patent families held by patent owners, the top 10 owners are all Chinese universities and research institutions, with an average of 48 patents per owner. Among the non-Chinese patent owners, the National University of Singapore and Seoul National University have the highest number of patents, both with an average of six patents per owner.

Figure 4.3.4.1 shows the top 10 AIE patent owners by the number of active patents. As the figure shows, the Hong Kong University of Science and Technology (HKUST) has the greatest overall strength in AIE patents (PAI=231). Whether it's the total number of patents or the average competitive impact of individual patents, the university surpasses other patent owners and is followed by South China University of Technology. With more than 100 AIE patents, both institutions are well ahead of others. Northwest Normal University has a notable patent competitive impact, with a CI of 1.4, second to HKUST (CI=1.9).

Notably, 9 out of the top 10 individual AIE patent owners are from Chinese universities (one is a research institute), which indicates that AIE material and technology patents are independent innovations of Chinese universities. Further implementation of recent national policies, laws, and regulations to promote the translation of scientific research can help these university patent owners to carry out technology transfer and commercialize inventions in various ways, which can lead to a bigger role in the industry. In addition, with the gradual increase in AIE academic–corporate collaborative research, understanding the ways to encourage corporations to join hands with academia in AIE patent development is an important issue for the advancement and diversity of AIE research.

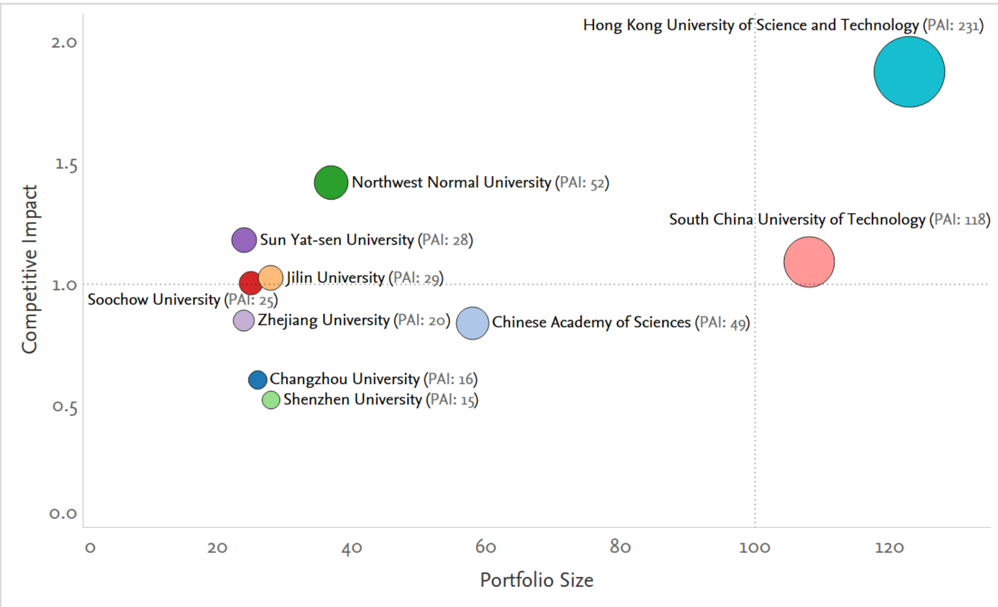

Figure 4.3.4.1 Patent competitive impact (CI) versus portfolio size, top 10 AIE patent owners by portfolio size, globally, as of December 31, 2021. The bubble size scales with the patent asset index (PAI). Patent search date: 2022/7/21, data source: LexisNexis® PatentSight® (Country code: CHN-China, JPN-Japan, KOR-Korea, SGP-Singapore, USA-USA)

Conclusion

❖ Led by China, the AIE field is an emerging research area with extensive collaboration globally. The field is growing at a rapid pace and delivering outstanding scholarly impact.

- Scholarly output of the global AIE field has been increasing annually since 2001. In fact, it has experienced exponential growth in the last decade. The number of published articles in the past 10 years accounted for 95.8% of all AIE publications. The normalized average citation impact (FWCI) of AIE publications reached 1.9, which is nearly twice the global average across disciplines. Reflecting the field's outstanding scholarly impact, 32.6% of all AIE publications were among the top 10% most highly cited articles. During the past two decades, AIE research has gradually gained widespread attention and has had far-reaching effects, led by scientists in several fields both nationally and internationally.

- China has led AIE research development: it has contributed to 74.6% of the total AIE publications in the past two decades, and 70% of the researchers involved in AIE research are from China; Hong Kong, China, has the highest output per researcher in the world, with an average of two publications per researcher; nine of the top 10 research institutions by AIE publication output are from China. Hong Kong University of Science and Technology and South China University of Technology have the highest number of publications in this field. These data show that originating in China, the field of AIE has led to the growth and development of this research domain in the Asia-Pacific region and globally, and that AIE research is truly a Chinese strength.

- The field of AIE is becoming a globalized research area: as AIE research grows, an increasing number of countries are entering the field, with 27.6% of the articles published through international/regional collaborations, and 98% of the articles from Hong Kong, China, published through these collaborations. Extensive international and regional collaborations have also led to articles with higher scholarly impact. As of 2021, a total of 76 countries/regions have published AIE-related research. Among them, Singapore contributed publications with high scholarly impact; India published numerous articles; and countries such as the United States, Japan, and Korea have all shown rapid growth in research in the field. Since the concept of AIE was first introduced in 2001, AIE has gradually grown from a new and original Chinese concept to a field of scientific research that has attracted an increasing number of researchers worldwide.

❖ The basic research of AIE spans several research subjects, such as chemistry, materials, optics, and physics. At the intersection of rapid

development and innovation, the field of AIE continues to expand into many areas, showing great application potential in optoelectronic devices, chemical sensing, biomedicine, and smart response technology. The field is currently in the global spotlight.

- The ASJC subject classification of global AIE articles reflects the evolution of the field from core subject areas such as chemistry, materials science, and chemical engineering to extended areas such as physics, biochemistry, genetic and molecular biology, and engineering. It has also demonstrated the field's expansion into new subject areas such as pharmacology, toxicology and pharmacy, environmental science, energy, and medicine, in recent years.

- The concept of AIE has also directly driven, developed, and influenced several related fields and inspired new ideas, such as the development of carbon dots, the application of circularly polarized luminescence (CPL) materials, the use of thermally activated delayed fluorescence (TADF) properties, and more.

- The field of AIE is under the global spotlight. Most of the major research topics covered in the AIE field have a prominence score of 99 or higher, meaning that they are more active than 99% of other research topics. The discoveries and applications in optoelectronic devices, chemical sensing, biomedical, and smart response technology are all within topics of prominence in the field.

As an original Chinese concept, AIE has changed the traditional research mindset, overturned the understanding of traditional luminescent technologies and materials, provided new ideas for the study of molecular luminescence mechanisms, and spurred development in both academia and industry, promoting and deepening the integration of interdisciplinary research. Thus, AIE research represents a type of innovative scientific endeavor with great potential for emerging technologies and industries, and is attracting worldwide attention.

❖ **Given the broad application of AIE research in organic optoelectronics and biomedicine, the main direction for future development will involve academic–corporate collaboration, research translation, and the industrialization of materials and devices.**

- Academic–corporate collaboration in the AIE field is still in its preliminary stage, but output of collaborative publications has grown rapidly in the last four years, showing a trend of rapid development. Although the scholarly impact of academic–corporate publications is lower compared to the field as a whole, publications between certain universities and corporations have high scholarly impact. Research in the field of AIE has room for growth with regard to academic–corporate collaboration.

- Publications related to AIE research have been cited by patents from the OLED, pharmaceutical, biotechnology, and chemical industries, indicating that AIE research has directly contributed to their technological innovation. This reflects the potential of AIE research for industrial application.

- The number of AIE patent applications entered a period of rapid growth in 2015, with China at the center of AIE material and technology innovation. Current AIE patents are mainly applied in the areas of chemistry, information technology, medical health, and electronics. Currently, universities lead the research and development of AIE-related patents, and fewer patents are developed by corporations. However, as the Chinese government introduces policies and regulations to accelerate research translation, it will also accelerate the technology transfer from universities to corporations. The application, exploration, and industrialization of AIE research are directions worth developing in the future.

The wide application of AIE materials in the fields of health, environment, chemistry, and precision medicine reflects the importance of AIE in both theoretical and practical applications. From basic research and laboratory development to industrial applications, AIE will penetrate many fields closely related to human life in the future, providing solutions with higher performance and lower cost.

In summary, this report offers a systematic overview of AIE research and its application through the analysis of scientific articles and patent data in the field. From a macroscopic viewpoint, it provides data to guide strategy and inform decision-making on the development of AIE scientific research. While this type of analytic report has certain inherent limitations, additional data analysis and expert insights are welcomed to further improve the report.

Appendix I

Keyword Sequence Methodology and Detailed Sequences

1. Keyword search of AIE research publications

Scientific articles in the AIE field are collected and classified in the Scopus database using a keyword sequencing method. The Elsevier research analytics team established the keyword sequence by combining expert-provided keywords through multiple iterations and supplementary testing. Based on the keywork sequence, the selected AIE articles were also screened by experts to eliminate noise. Taken together, the keyword sequence is derived from objective data supplemented by manual identification by experts. The keyword sequence pinpointed the title, abstract and keywords (including index keywords and author keywords) of each article to form the collection of AIE publications.

The keyword search for the AIE research publications is as follows.

TITLE-ABS-KEY (({aggregate induced emission} OR {aggregated induced emission} OR {aggregated induced emissions} OR {aggregated-induced emission} OR {aggregate-induced emission} OR {aggregation induced emission} OR {aggregation induced emissions} OR {aggregation induce emission} OR {aggregation induced emissive} OR {aggregation induced-emission} OR {aggregation induced-emissions} OR {aggregation induces emission} OR {aggregation-induce emission} OR {aggregation-induced emission} OR {aggregation-induced emissions} OR {aggregation-induced emissive} OR {aggregation-induced/-enhanced emission} OR {aggregation-induced-emission} OR {aggregation-induced-emissions} OR {aggregation-induced-emissive} OR {aggression-induced emission} OR {aggregation–induced emission} OR {Clustering-triggered emissions} OR {Clustering triggered emissions} OR {Clustering-triggered emission} OR {Clustering triggered emission} OR {clusterization triggered emission} OR {clusterization-triggered emission} OR {cluster-triggered emission} OR {cluster-triggered-emission} OR {Aggregation-induced delayed fluorescences} OR {Aggregation induced delayed fluorescences} OR {Aggregation-induced delayed fluorescent} OR {Aggregation induced delayed fluorescent} OR {Aggregation-induced delayed fluorescence} OR {Aggregation induced delayed fluorescence} OR {crystallisation-induced emission} OR {crystallization-induced-emission} OR {Crystallization-induced emissions} OR {Crystallization induced emissions} OR {Crystallization-induced emission} OR {Crystallization induced emission} OR {crystallization-induced emissive} OR {crystalization-induced emission} OR {crystalization induced emission} OR {Aggregation-induced Phosphorescent} OR {Aggregation-induced phosphorescence} OR {Aggregation induced phosphorescence} OR {Aggregation induced Phosphorescent} OR {Clusteroluminescence} OR {Clusteroluminescent} OR {AIEgen} OR {AIEgens} OR {AIE dots} OR {AIEdots} OR {AIE dot} OR {AIEdot} OR {AIE-dots} OR {AIE-dot} OR {AIE light-up probes} OR {AIE light-up probe} OR {restriction of intramolecular motion} OR {restrictions of intramolecular motions} OR {restriction of intramolecular motions} OR {Tetraphenylethene} OR {Tetraphenylethylene} OR {Tetraphenyl ethylene} OR {Tetraphenyl ethene} OR {aggregation emission enhancement} OR {Aggregation-emission-enhancement} OR {Aggregate-enhanced emission} OR {Aggregate enhanced emission} OR {Aggregate-enhanced emissions} OR {Aggregation enhanced emission} OR {Aggregation-enhanced emission} OR {aggregation enhanced emissive} OR {AIE Metallocage} OR {AIE Metallocages} OR {AIE Photosensitizing} OR {AIE Photosensitizer} OR {AIE Photosensitizers} OR {AIE-photosensitizers} OR {AIE-photosensitizer} OR {AIE polymers} OR {AIE polymer} OR {AIE-polymers} OR {AIE-polymer} OR {restriction of intramolecular restrictions} OR {restriction of intramolecular restriction} OR {restriction of intramolecular vibration} OR {restriction of intramolecular vibrations} OR {restriction of intramolecular twist} OR {aggregation enhanced ROS generation} OR {aggregation-enhanced ROS Generation} OR {aggregation-enhanced reactive oxygen species generation} OR {aggregation enhanced reactive oxygen species generation} OR {vibration induced emission} OR {Vibration-induced Emission} OR {Vibration-Induced-Emission} OR {vibration-induced emissions} OR {aggregation-induced enhanced emission} OR {aggregation-induced enhanced emissions} OR {Aggregation-induced enhancement} OR {aggregation induced enhancement} OR {Aggregation-induced-enhancement} OR {aggregation-induced enhancements} OR {aggregation induced blue-shifted emission} OR {aggregation-induced blue-shifted emission} OR {Aggregation Induced Blue Shifted Emission} OR {aggregation induced blue shifted emissions} OR {aggregation-induced dual phosphorescence} OR {Aggregation-Induced Dual-Phosphorescence} OR {AIE mechanism} OR {AIE mechanisms} OR {AIE properties} OR {AIE property} OR {Restriction of intramolecular rotation} OR {polymerization induced emission} OR {polymerization-induced emission} OR {Polymerization-induced emissions} OR {polymerization induced emissions} OR {Assembly-induced Emission} OR {Assembly induced Emission} OR {assemblies induced emission} OR {aggregation-induced circularly polarized luminescence} OR {aggregation induced circularly polarized luminescence} OR {crystallization-induced dual emission} OR {crystallization induced dual emission} OR {anti-aggregation-caused quenching} OR {Anti-ACQ} OR {dual-state fluorescence} OR {dual state fluorescence} OR {dual-state luminescence} OR {dual state luminescence} OR {organic persistent room-temperature phosphorescence} OR {organic persistent room temperature phosphorescence} OR {aggregation-induced intersystem crossing} OR {aggregation induced intersystem crossing} OR {Aggregation induced two-photon} OR {aggregation-induced two-photon} OR {Aggregation induced three-photon} OR {aggregation-induced three-photon} OR {non-traditional luminescence} OR {non-traditional luminescent} OR {non conventional luminescence} OR {non conventional luminescent} OR {Aggregation-induced generation of reactive oxygen species} OR {Aggregation induced generation of reactive oxygen species} OR {Aggregation-enhanced Theranostics} OR {Aggregation enhanced Theranostics} OR {rigidification induced emission} OR {rigidification-induced emission} OR {aggregation induced third harmonic generation enhancement} OR {force induced luminescence} OR {force induced luminescent} OR {force-induced luminescence} OR {force-induced luminescent} OR {force-induced emission} OR {force induced emission} OR {aggregation-induced chirality} OR {Aggregation induced chirality} OR {aggregates-induced chirality} OR {aggregate state molecular motion} OR {aggregation state molecular motion} OR {intramolecular motion-induced photothermy} OR {solid-state molecular motion} OR {solid-state molecular motions} OR {Solid state molecular motion} OR {solid state molecular motions} OR {solid state: Molecular motion} OR {dual-state emissions} OR {dual state emissions} OR {dual-state emission} OR {dual state emission} OR {mechanochromic luminescence} OR {mechanochromic luminescent} OR {bioAIEgen} OR {bioaiegens} OR {aggregate-state emission} OR {aggregate-state emissions} OR {aggregate state emission} OR {aggregate state emissions} OR {aggregate states emission} OR {AIE characteristics} OR {AIE characteristic} OR {AIE molecules} OR {AIE molecule} OR (({aggregation induce} OR {Aggregation-induced} OR {Aggregation induced} OR {aggregation-induce} OR {aggregations induce}) AND ({mechanoluminescence} OR {mechanoluminescent} OR {Polymerization-induced self-assembly} OR {Polymerization induced self-assembly} OR {polymerisation-induced self-assembly} OR {polymerisation induced self-assembly} OR {Polymerization-induced self assembly} OR {Polymerization induced self assembly} OR {polymerisation-induced self assembly} OR {polymerisation induced self assembly} OR {coordination polymerization} OR {coordination polymerisation} OR {coordination polymerizations} OR {coordination, polymerization} OR {coordination-polymerization} OR {Electrochemiluminescence} OR {Electrochemiluminescent})) OR (({aggregation enhance} OR {aggregations enhance} OR {aggregation enhanced} OR {aggregation-enhanced}) AND ({theranostics} OR {Theranostic} OR {photodynamic} OR {photodynamics})) OR (({rigidification induce} OR {rigidification-induced} OR {rigidification induced}) AND ({emission} OR {emissions})) OR (({crystallisation-induced} OR {crystallization-induced} OR {crystallisation induced} OR {crystallization induced}) AND ({emission} OR {emissions})) OR (({aggregation-induced} OR {aggregation-induce} OR {aggregation induce} OR {aggregation induced}) AND ({phosphorescent} OR {phosphorescence})) OR {AIE-active} OR {AIE active} OR {aggregation-induced luminescence} OR {aggregation-induced luminescences} OR {aggregation induced luminescence} OR {aggregation induced luminescences} OR {aggregation-induced fluorescence} OR {aggregation-induced fluorescences} OR {aggregation-induced fluorescent} OR {aggregation induced fluorescence} OR {aggregation induced fluorescences} OR {aggregation induced fluorescent} OR (({Crystallization-induced} OR {Crystallization induced}) AND ({phosphorescence} OR {phosphorescences} OR {phosphorescent})) OR {Aggregation-enhanced fluorescence} OR {Aggregation enhanced fluorescence} OR {Anti-Kasha} OR {Anti Kasha} OR {Clustering-induced emissions} OR {Clustering induced emissions} OR {Clustering-induced emission} OR {Clustering induced emission} OR {clusterization induced emission} OR {clusterization-induced emission} OR {cluster-induced emission} OR {cluster-induced-emission} OR (({polymer fluorescent } OR {polymer fluorescents}) AND ({chemosensors} OR {chemosensor})) OR (({solid-state} OR {solid state}) AND {luminescence} AND {stacking} AND {molecular}) OR {Mechanically induced luminescence} OR {Mechanically-induced luminescence} OR {luminescent liquid crystal} OR {luminescent liquid crystals} OR {piezochromic luminescent} OR (({aggregation induce} OR {Aggregation-induced} OR {Aggregation induced} OR {aggregation-induce} OR {aggregations induce}) AND ({two-photon} OR {two photon} OR {three-photon} OR {three photon})) OR (({aggregation induce} OR {Aggregation-induced} OR {Aggregation induced} OR {aggregation-induce} OR {aggregations induce}) AND ({fluorescent} OR {fluorescents}) AND ({sensor} OR {sensors}))))) OR (TITLE-ABS-KEY ({AIE} AND ({OLED} OR {OLEDs} OR {organic light emitting diode} OR {organic light emitting diodes} OR {organic light-emitting diode} OR {organic light-emitting diodes} OR {Silole} OR {Siloles} OR {(circularly polarized) luminescence} OR {Circularly Polarised Luminescence} OR {Circularly polarized luminescence} OR {Circularly-polarized luminescence} OR {CPL} OR {MOFs} OR {MOF} OR {metal organic framework} OR {metal organic frameworks} OR {metal-organic framework} OR {metal-organic frameworks} OR {metal-organic-framework} OR {metal-organic-frameworks} OR {metalorganic Frameworks} OR {mechanochromic system} OR {tetraphenythiophene} OR {maleimide} OR {maleimides} OR {cyanostilbene} OR {cyanostilbenes} OR {9,10-divinylanthracene} OR {9,10-Divinylanthracenes} OR {multi aryl pyrroles} OR {multi-aryl pyrroles} OR {multi aryl pyrrole} OR {multi-aryl pyrrole} OR {triphenylpyrrole} OR {triphenylpyrroles} OR {hexaphenyl-1 3-butadienes} OR {hexaphenyl-1,3-butadiene} OR {multiaryl-1,3-butadiene} OR {multiphenyl-1,3-butadiene} OR {tetraphenyl-1,3-butadiene} OR {tetraphenyl-1,3-butadienes} OR {OFET} OR {OFETs} OR {organic field effect transistor} OR {organic field-effect transistor} OR {organic field-effect transistors} OR {organic field effect transistors} OR {organic field-effect-transistor} OR {organic field-effect-transistors} OR {(organic) field-effect transistors} OR {organic-field-effect transistor} OR {organic-field-effect transistors} OR {electroluminescence} OR {electroluminescent} OR {electroluminescences} OR {electroluminescents} OR {photolithography} OR {highly refractive materials} OR {highly refractive material} OR {photothermal therapies} OR {photothermal therapy} OR {photothermal/photodynamic therapies} OR {photodynamic therapies} OR {photo-dynamic therapy} OR {photodynamic therapy} OR {Photodynamic-therapy} OR {anti-counterfeiting} OR {Anticounterfeiting} OR {anti-counterfeitings} OR {anti-counterfeit} OR {anti counterfeiting} OR {dark state} OR {dark-state} OR {dark states} OR {dark-states} OR {twisted intramolecular charge transfer} OR {twisted intra-molecular charge transfers} OR {twisted intramolecular charge-transfer} OR {twisting intramolecular charge transfer} OR {twisting-intramolecular-charge-transfer} OR {TICT} OR {TICTs} OR {Excited State Intramolecular Proton Transfer} OR {excited state intramolecular proton-transfer} OR {Excited-state Intramolecular Proton Transfer} OR {excited-state 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Imaging} OR {through-space conjugation} OR {through space conjugation} OR {through space interaction} OR {through space interactions} OR {through-space interactions} OR {through-space interaction} OR {through-space interaction} OR {'through-space' interaction} OR {through-space interactions} OR {through-space-interactions} OR {image-guided therapy} OR {image guided therapy} OR {image-guided therapies} OR {image guided therapies} OR {photovoltaic cell} OR {photovoltaic cells} OR {molecular design} OR {molecular designs} OR {molecular-design} OR {molecular-designs} OR {molecular rotor} OR {molecular rotors} OR {Solid State Emission} OR {Solid State Emissions} OR {Solid-state Emission} OR {Solid-state Emissions} OR {Hyperbranched Polymers} OR {Hyperbranched Polymer} OR {multimodal Therapy} OR {multimodal therapies} OR {multimodal-therapy} OR {multimodal-therapies} OR {Theranostics} OR {Theranostic} OR {phototheranostics} OR {phototheranostic} OR {cell tracking} OR {cell-tracking} OR {cells tracking} OR {cells-tracking} OR {immunological therapy} OR {immunological therapies} OR {Structure Property} OR {Structure-property} OR {structure properties} OR {structure-properties} OR {Structural Property} OR {Structural-property} OR {Structural Properties} OR {Structural-Properties} OR {Hot Exciton} OR {Hot Excitons} OR {Hot-Exciton} OR {Hot-excitons} OR {Photoacoustic} OR {photoacoustics} OR {molecular tailoring} OR {2D materials} OR {2D material} OR {Molecular Motions} OR {Molecular Motion} OR {Microcapsule} OR {Microcapsules} OR {Afterglow} OR {Afterglows} OR {aggregated state} OR {aggregated states} OR {mechanoluminescence} OR {mechanoluminescent} OR {Polymerization-induced self-assembly} OR {Polymerization induced self-assembly} OR {polymerisation-induced self-assembly} OR {polymerisation induced self-assembly} OR {Polymerization-induced self assembly} OR {Polymerization induced self assembly} OR {polymerisation-induced self assembly} OR {polymerisation induced self assembly} OR {coordination polymerization} OR {coordination polymerisation} OR {coordination polymerizations} OR {coordination, polymerization} OR {coordination-polymerization} OR {room temperature phosphorescence} OR {room-temperature phosphorescence} OR {room-temperature-phosphorescence} OR {RTP} OR {delay fluorescence} OR {delay fluorescent} OR {delayed fluorescence} OR {delayed fluorescences} OR {delayed fluorescent} OR {delayed-fluorescence} OR {delayed-fluorescences} OR {delayed-fluorescent} OR {delayer fluorescence} OR {delayer fluorescent} OR {ligand charge transfer} OR {ligand charge-transfer} OR {ligand-charge-transfer} OR {ligand charge transfers} OR {ligand-charge transfer} OR {near infrared} OR {near-infrared} OR {hydrogel} OR {hydrogels} OR {sensor} OR {sensors} OR {Fluorescence} OR {Fluorescent} OR {Fluorescences} OR {Fluorescents} OR {schiff base} OR {Schiff Bases} OR {Schiff-base} OR {Schiff's base} OR {Schiff's bases} OR {Schiff-bases} OR {Schiffs base} OR {Schiff' base} OR {Schiff' bases} OR {schiffs' base} OR {Schiff's-base} OR {liquid crystal} OR {liquid crystalline} OR {liquid crystallinity} OR {liquid crystals} OR {liquid-crystal} OR {liquid-crystals} OR {Stimuli response} OR {Stimuli responses} OR {Stimuli responsive} OR {Stimuli responsiveness} OR {stimuli-response} OR {Stimuli-responses} OR {Stimuli-responsive} OR {Stimulus response} OR {Stimulus responses} OR {Stimulus responsive} OR {Stimulus responsiveness} OR {Stimulus-response} OR {Stimulus-responses} OR {Stimulus-responsive} OR {nonlinear optical} OR {non-linear optical} OR {nonlinear optics} OR {nonlinear-optics} OR {nonlinear-optical} OR {Nonlinear, optics} OR {luminescence} OR {luminescent} OR {luminescences} OR {luminescents} OR {Micelles} OR {Micelle} OR {solar cells} OR {solar cell} OR {solar-cell} OR {solar-cells} OR {two-photon} OR {two photon} OR {three-photon} OR {three photon}))) AND PUBYEAR > 2000 AND PUBYEAR < 2022

2. Keyphrase search of publications from the nine research areas

The scientific articles in the nine areas in Chapter 3, Section 2 were collected and classified in the Scopus database with a keyphrase sequencing method. The Elsevier research analytics team used the keyphrase sequence to locate expert-provided keyphrases in the title, abstract and keywords (containing index keywords and author keywords) of each publication to establish the nine research areas. The keyphrase search for the nine field collections is as follows.

(1) Thermally activated delayed fluorescence (TADF) field

TITLE-ABS-KEY ({thermal activated delayed fluorescence} OR {thermal activated delay fluorescence} OR {thermal activated delay fluorescent} OR {thermal activated delayed fluorescent} OR {Thermal activation delayed fluorescence} OR {thermal assisted delayed fluorescence} OR {thermal-activated delayed fluorescence} OR {thermally actively delayed fluorescence} OR {thermally actively delayed fluorescent} OR {thermally activated delay fluorescence} OR {thermally activated delay fluorescent} OR {thermally activated delayed fluorescence} OR {thermally activated delayed fluorescences} OR {thermally activated delayed fluorescent} OR {thermally activated delayed-fluorescence} OR {thermally activated delayed-fluorescences} OR {thermally activated delayed-fluorescent} OR {thermally activated delayer fluorescence} OR {thermally activated delayer fluorescent} OR {thermally active delayed fluorescence} OR {thermally active delayed fluorescent} OR {thermally activated (E-type) delayed fluorescence} OR {thermally activated delayed (E-type) fluorescence} OR {thermally activated, delayed fluorescence} OR {thermally-activated delayed fluorescence} OR {thermally-activated delayed fluorescences} OR {thermally-activated delayed fluorescent} OR {thermally-activated delayed-fluorescent} OR {thermally-activated, delayed fluorescence} OR {thermally-activated-delayed-fluorescence})

(2) Room temperature phosphorescence field

TITLE-ABS-KEY ({room temperature phosphorescence} OR {room-temperature phosphorescence} OR {room-temperature-phosphorescence})

(3) Mechanoluminescence field

TITLE-ABS-KEY ({mechanoluminescence} OR {mechanoluminescent} OR {mechanochromism})

(4) Carbon dots field

TITLE-ABS-KEY ({carbon dots} OR {carbon dot} OR {carbon-dot} OR {carbon-dots})

(5) Circularly polarized luminescence

TITLE-ABS-KEY ({Circularly polarized luminescence} OR {Circularly Polarised Luminescence} OR {Circularly-polarized luminescence} OR {(circularly polarized) luminescence})

(6) Bioprobe field

TITLE-ABS-KEY ({bio-probe} OR {bioprobes} OR {bio-probes} OR {bioprobe})

(7) Luminescent solar concentrator field

TITLE-ABS-KEY ({Luminescent solar concentrator} OR {luminescent solar concentrators} OR {Luminescent-solar-concentrator} OR {luminescent-solar-concentrators} OR {Luminescence Solar concentrator} OR {Luminescence solar concentrators} OR {Luminescence-solar-concentrator} OR {Luminescence-solar-concentrators})

(8) Excited state intramolecular proton transfer (ESIPT) field

TITLE-ABS-KEY ({excited state intramolecular proton transfer} OR {excited state intramolecular proton-transfer} OR {excited-state intramolecular proton transfer} OR {excited - state intramolecular proton transfer} OR {excited-state intramolecular proton transfers} OR {excited-state intramolecular proton-transfer} OR {excited-state-intramolecular-proton-transfer} OR {excited-state intramolecular-proton-transfer} OR {ESIPT})

(9) Twisted intramolecular charge transfer (TICT) field

TITLE-ABS-KEY ({twisted intramolecular charge transfer} OR {twisted intra-molecular charge transfers} OR {twisted intramolecular charge-transfer} OR {twisting intramolecular charge transfer} OR {twisting-intramolecular-charge-transfer} OR {twisted-intramolecular-charge-transfer} OR {TICT})

Appendix II

Scopus database

This report uses Scopus, which is Elsevier's database of peer-reviewed publications abstracts and citations, covering 77.3 million articles in over 39,000 journals, book series, and conference proceedings, by 5,000 publishers, in approximately 105 countries.

Scopus has multilingual and global coverage: about 46% of the titles in Scopus are published in languages other than English (or in both English and other languages). In addition, more than half of its content is from outside of North America, presenting research from countries in Europe, Latin America, Africa, and the Asia-Pacific region.

Scopus covers all major research areas, with about 13,300 publications in natural sciences, 14,500 in health sciences, 7,300 in life sciences, and 12,500 in social sciences (including about 4,000 publications on subjects related to the arts and humanities). The publications included are mainly serials (journals, trade journals, book series and conference materials), as well as a considerable number of conference papers covered as stand-alone conference proceedings (a major dissemination system, particularly in computer science). Recognizing that many publications (particularly social sciences and arts and humanities) are published in book form, Scopus began to increase book coverage in 2013. As of 2018, Scopus included 1.75 million books, including 400,000 in social sciences, and 290,000 in humanities and arts.

In addition, Scopus includes approximately 7.89 million open access articles, with over 5,500 Gold OA journals covered.

Scopus includes approximately 43.7 million patent records from five major patent offices: the United States Patent and Trademark Office (USPTO), the European Patent Office (EPO), the Japan Patent Office (JPO), the United Kingdom Intellectual Property Office (UKIPO) and the World Intellectual Property Organization (WIPO).

Data in Scopus is updated on a daily basis, with approximately 10,000 publication updates every day.

Appendix III

SciVal database

Elsevier's next-generation SciVal scientific data analysis platform provides fast and easy access to research from more than 12,000 research institutions and 230 countries worldwide. As a ready-to-use platform with multiple features and flexibility, SciVal enables users to easily navigate through the research landscape and delivers meaningful analysis and insights into research performances. Elsevier also works with many of the world's leading institutions year-round through SciVal Spotlight and SciVal Strata, which helps to refine SciVal.

1. Data sources

Based on Scopus, SciVal has access to Scopus' data from 1996 to today, covering over 48 million records, including 21,000 articles in serials from 5,000 publishers. These records include:

- More than 22,000 peer-reviewed journals
- 360 trade publications
- 1100 book series
- 5.5 million conference materials

2. Metrics

SciVal offers a wide range of metrics that meet industry standards and are easily interpreted, including Snowball metrics, standardized metrics recognized and developed by higher education institutions to help inform strategic decision-making

Appendix IV

LexisNexis® PatentSight® Patent Database and Patent Search

LexisNexis® PatentSight® is a business intelligence-based database that integrates patent search, assessment, and analytics. The system is dedicated to helping companies and research institutions to obtain in-depth analysis on the impact, quality and value of patents and patent portfolios/patent families. Currently, LexisNexis® PatentSight® documents patent records from patent licensing authorities in 115 countries/regions.

LexisNexis® PatentSight® owns the global patent evaluation tool, Patent Asset Index™. This tool, developed through systems science, is exclusively offered by LexisNexis® PatentSight®. It can identify impactful patents from the database and serve as a prerequisite for reliable patent analysis. In addition, the tool can analyze patent portfolios against competitors, suppliers, customers, specified technology areas, and new market entrants to identify potential opportunities and improvements.

For more information, please visit https://www.lexisnexisip.com/solutions/ip-analytics-and-intelligence/patentsight/

1. AIE Patent Search Purpose

The purpose of the patent search is to locate AIE-related patents through the LexisNexis® PatentSight® tool, which documents patent records from patent licensing authorities in 115 countries/regions. The analysis on AIE-related patents can reflect the current state of prior art in the AIE field.

2. AIE Patent Search Strategy

Since AIE is an emerging research field, there is no exact classification number in the existing patent classification system. Thus, the search uses keywords in AIE research for patent search as a start, while supplementing that with cooperative patent classification (CPC) as a limiter to conduct a comprehensive search. The AIE patent search is divided into four steps: core patent search, expanded patent search, supplementary search, and refinement through application date.

(1) Core patent search:

The purpose of a core patent search is to conduct a comprehensive investigation to identify AIE research by pinpointing specific keywords within certain sections, such as the title, abstract, and claim in patent documents, without the CPC as a limiter. Since the three sections contain the core information about a patent, including an overview of the invention, the novelty of the creation, and the scope of patent protection, patents with keywords related to AIE research can be considered as AIE core patents.

Since the search of core patents is mainly determined by keywords, which affect the accuracy and comprehensiveness, the workflow of keyword selection for AIE patents is detailed below.

The selection of keywords should express the features of the research subjects within the field of AIE; in addition, the keywords should be general and universal enough to retrieve AIE-related patents through a certain number of keywords. Based on the two points above, the report referenced the workflow of AIE publication search, selecting keywords from four areas (AIE phenomenon, AIE mechanism, AIE material properties, and AIE applications) that appeared in a large number of AIE articles. Taking the writing style and language of patent documents into consideration, the report selected 33 AIE patent search keywords. The details of AIE keyword search expression are shown in Table 1.

Table 1: Thirty-three AIE core patent search keywords

AIE Core Patent Search Keyword Expressions

((aggregat* SEQ2 (induce% SEQ2 emissi*))	(AIE propert*)
(aggregat* SEQ2 (induce% SEQ2 enhance*))	(AIE compound%)
(aggregat* SEQ2 (induce% SEQ2 phosphescen*))	(AIE effect%)
(aggregat* SEQ2 (induce% SEQ2 fluescen*))	(AIE performance%)
(aggregat* SEQ2 (induce* SEQ2 luminescen*))	(AIE molecule%)
(aggregat* SEQ2 (enhance* SEQ2 emissi*))	(AIE SEQ2 TADF)
(Aggregat* SEQ2 (enhance* SEQ2 fluescen*))	(AIE material%)
(crystalli* SEQ2 (induce* SEQ2 emissi*))	(Aggregation enhance% ROS generation)
(Cluster* induce% emission%)	(AIE photosensiti?er)
(polymeri* SEQ2 (induce* SEQ2 emission%))	(AIE SEQ2 probe%)
(assemb* SEQ2 (induce* SEQ2 emissi*))	(restriction% of intra_molecular motion%))
(AIEgen%)	(aggregat* SEQ2 (induce% SEQ2 emitting))
(AIE active)	(AIE AND (Aggregat* SEQ2 quenching))
(AIE_dot%)	(AIE Fluescen*)
(AIE Photosensiti*)	(AIE SEQ2 fluorophore%)
(AIE polymer%)	(AIE Characteristic%)
(AIE lumino*)	

(2) Expanded Patent Search:

Core patent search was limited to specific sections in the patent, such as the title, abstract, and claim. To expand the scope of the search and retrieve relevant patents that may have fallen through the cracks, the report extended its AIE keyword[38] search into the description section in patent

[38] The keyword "AIE compound" was removed from the extended search due to the introduction of noisy articles in the extended search.

documents. Description mainly lists or discusses the technological features of the invention and serves as supplementary information to the main technological subject matter. This expansion can introduce patents that are not in the field of AIE, so the reports used CPC (Level 4 Technology Cluster) as a perimeter for the results. To be specific, the report limited the expanded search based on the top nine CPC level 4 technology clusters with the most AIE patent from core patent search (1). For more specifics, see below.

Results for the AIE patents from the core patent search were distributed in 479 CPC level 4 technology clusters. Among them, the top nine CPC level 4 technology clusters with the most patents are at the center of AIE patents, accounting for 76% of the AIE core patents. After the top nine, each new CPC level 4 technology cluster has less than three additional patents. Thus, the report concludes that the top 9 CPC level 4 technology clusters can be regarded as highly relevant to AIE core patents. The nine CPC were also consistent with the results of the classification obtained by searching "aggregation induced emission" in the European Patent Office. Table 2 shows the nine CPC level 4 technology cluster numbers and their names.

Table 2. List of nine AIE-related CPC class level 4 technology cluster.

CPC Level 4 Technology Cluster Number	Cluster Name
C09K 11	Luminescent, e.g. electroluminescent, chemiluminescent materials
C09K2211	Chemical nature of organic luminescent or tenebrescent compounds
G01N 21	Investigating or analysing materials by the use of optical means, i.e. using infra-red, visible or ultra-violet light G01N3/00-G01N19/00 take precedence
G01N2021	General arrangement of respective parts
A61K 49	Preparations for testing in vivo
A61K 41	Medicinal preparations obtained by treating materials with wave energy or particle radiation ; Therapies using these preparations
A61P 35	Antineoplastic agents
H01L 51	Solid state devices using organic materials as the active part, or using a combination of organic materials with other materials as the active part | Processes or apparatus specially adapted for the manufacture or treatment of such devices, or of parts thereof devices consisting of a plurality of components formed in or on a common substrate H01L27/28; thermoelectric devices using organic material H01L35/00, H01L37/00; piezoelectric, electrostrictive or magnetostrictive elements using organic material H01L41/00
G01N 33	Investigating or analysing materials by specific methods not covered by groups G01N1/00 - G01N31/00

(3) Supplementary search:

"Institute of Advanced Research on Aggregate Induced Luminescence, South China University of Technology, Guangdong Province," "Hong Kong University of Science and Technology," and "South China University of Technology" were added as patent owners in the supplementary search. The team searched for title, abstract, claim and description that includes the keyword "AIE" to complement the core patent search and expanded patent search.

(4) Refining the search through application date:

The results from the core patent search, the expanded search, and the supplementary search were combined. On this basis, the search was further restricted to "patent application date occurred after January 1, 2001" to ensure that all the retrieved AIE-related patent applications occurred on or after January 1, 2001. The search resulted in an AIE patent portfolio for analysis.

Appendix V

Glossary of terms

Scholarly output: All publications, including journal publications, conference proceedings, review publications and publication series, on the assessed subject, representing the scientific research output on the subject over a fixed period of time.

Citation count: It refers to the number of citations for all the articles of the assessed subject within a fixed period. To a certain extent, it reflects the scholarly impact of the assessed subject's publications. However, it should be noted that articles published more recently will have a lower total number of citations due to less accumulation time compared to articles published earlier.

Field Weighted Citation Impact (FWCI): FWCI is an indicator of the citation impact of a subject's publications. Compared to the total citation count, FWCI considers the number of citations received by the subject's publications and the number of citations received by the same type of publications (same publication year, same publication type, and same subject area). The FWCI can better control for the differences in the number of citations caused by the scale of scholarly output, the various citation patterns of different subjects, and differences in publication years. If the FWCI is 1, it means that the number of citations of the evaluated article is exactly equal to the average of the same type of articles in the whole Scopus database.

The formula for calculating the **FWCI** is as follows.

$$FWCI = \frac{C_i}{E_i}$$

C_i indicates the number of citations received by the article.

E_i indicates the average number of citations for all articles of the same type in the year of publication as well as the following 5 years.

If a collection of publications contains N articles, then the FWCI of this collection can be calculated by the following formula.

$$\overline{FWCI} = \frac{1}{N}\sum_{i=1}^{N}\frac{C_i}{E_i}$$

N denotes the number of articles in the collection of publications that are indexed in the Scopus database.

The FWCI uses a 5-year time window for citation counts. For example, the FWCI mean for 2012 publications is calculated based on citations from 2012 to 2017. If an article was published less than 5 years ago, all citations from the date of data extraction were used in the calculation.

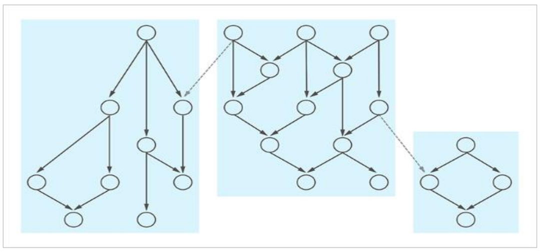
Compound Annual Growth Rate (CAGR): is the annual growth rate over a given period. It is calculated as the n-square root of the total percentage growth rate. n is equal to the number of years in the period in question by formula: (current value/starting value)^(1/number of years) - 1.

Academic research collaboration consists of three categories: international/regional, domestic and institutional collaboration, of which:

- **International/Regional Collaborations** are articles published by multiple authors, in which at least one of the authors is affiliated with a foreign/regional research institution.
- **National Collaborations** are articles published by multiple authors, none of whom are affiliated with a foreign research institution, in which the affiliations of the authors include at least two different institutions in the same country.
- **Institutional Collaborations** are articles published by multiple authors, none of whom are affiliated with foreign research institutions or other domestic research institutions. All of the authors are affiliated with the same institution.
- **Single Authorship:** means that the publication is published by one author, and this item is presented as a comparison item.

Academic–Corporate Collaborative Publications: the articles are published by multiple authors, at least one of whom is affiliated with an academic institution and at least one of whom is affiliated with a corporation.

Research Topics: a collection of articles that share a common research interest, meaning that the research content has the same focus. In the Scopus database, all publications are categorized into approximately 96,000 research topics by an algorithm based on direct citation. Publications within the same research topic are strongly related to each other through citation while publications with a weaker citation tie will be grouped into a different topic. A detailed schematic for research topic clustering is listed below.



Circles indicate articles, solid arrows indicate strong citation relationships, and dashed arrows indicate weak citation relationships. Articles with strong citation relationships are grouped under the same research topic, and articles with weak citation relationships are grouped under different research topics.

Topic Prominence: This indicator is linearly calculated using three indicators of topics: number of citations, number of views in Scopus, and average journal factor CiteScore, which reflects the attention, popularity, and development momentum of the topic by scholars worldwide, and the prominence is positively correlated with research funding and grants. By looking for topics with high prominence, we can guide researchers and research managers to get more funding. More information on Topics and topic prominence is available at:

https://www.elsevier.com/solutions/scival/releases/topic-prominence-in-science

https://service.elsevier.com/app/answers/detail/a_id/28428/

Portfolio Size: indicates the number of patent families attributable to an entity—for example, a country or region, or a topic cluster, or the overall total. When calculated for a country or region, it is attributed based on the affiliation addresses of patents' listed inventors.

The Patent Asset Index™, or PAI, is the sum of the Competitive Impacts of all patent families in a portfolio. In general, the higher the value, the more impactful the patent is. This index is widely used in intellectual property departments, competitive intelligence, competition authorities, and investor relations.

Competitive Impact (CI) is calculated on patent family level and represents the relative business value of each patent family. The value is calculated by multiplying Technology Relevance and Market Coverage. Each patent (family) is assigned a CI value. In the analysis, the CI value of a patent portfolio is the average CI value of the individual patents.

Technology Relevance (TR) measures the importance of a patent family (invention) for technological development. It is calculated based on the number of worldwide prior art citations received from other patent families. It also takes into account the age of the patent, patent office citation practices, and citation differences between technology fields to conclude the impact of a patent family. In other words, if the TR value is 2 for a patent family, it means that a patent family is twice as relevant for technological developments as an average patent family in the same technology field and of the same age.

Market Coverage (MC) is calculated at the patent family level and indicates the size of the global market in which the patent family is protected. The calculation takes into account the number of countries in which the evaluated patent (family) is filed and the gross national income of the countries in the same year based on data from World Bank. It also considers the legal status of each patent (family), including filed, granted, or inactive.

Appendix VI

Description of benchmark countries and regions

The countries and regions used for benchmarking analysis in this report include China (including Hong Kong, Macao and Taiwan), the United States, Japan, Singapore, India, the European Union (EU) region, the Asia-Pacific region, North America and the world.

The European region is comprised of 28 countries, including Austria, Belgium, Bulgaria, Cyprus, Croatia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

The Asia-Pacific region includes 58 countries and areas other than Chinese mainland in the following order: India, Japan, Australia, South Korea, Malaysia, Singapore, Indonesia, Pakistan, New Zealand, Thailand, Viet Nam, Bangladesh, Philippines, Kazakhstan, Sri Lanka, Georgia, Nepal, Armenia, Azerbaijan, Uzbekistan, Brunei Darussalam, Mongolia, Cambodia, Myanmar, Fiji, Kyrgyzstan, Laos, Papua New Guinea, New Caledonia, Tajikistan, French Polynesia, Korea, Bhutan, Guam, Solomon Islands, Maldives, Vanuatu, Samoa, Timor-Leste, Turkmenistan, Federated States of Micronesia, Palau, Tonga, American Samoa, Cook Islands, Kiribati, Marshall Islands, Northern Mariana Islands, Turks and Caicos Islands, Tuvalu, Nauru, Niue, United States Minor Outlying Islands, Wallis and Futuna, Norfolk Island, Hong Kong, Macao and Taiwan.

The North American region includes both the United States and Canada.

The domestic regions in this report include: Hong Kong, China; Taiwan, China; Yangtze River Delta region (Shanghai, Jiangsu, Zhejiang, and Anhui); Pearl River Delta region (Guangdong); and Beijing, Tianjin, and Hebei region.

Appendix VII

Description of ASJC subject areas

The main subject classification used by Scopus is the All Science Journal Classification (ASJC). This classification method is used by Elsevier's internal experts to classify scientific publications in the entire Scopus library at the journal level, into 27 major categories and 334 sub-categories. The 27 major categories are shown in the table below.

Scopus Subject Classification - 27 ASJC subject areas

General (multidisciplinary journals[39])	Immunology and Microbiology
Agricultural and Biological Sciences	Materials Science
Arts and Humanities	Mathematics
Biochemistry, Genetics and Molecular Biology	Medicine
Business, Management and Accounting	Neuroscience
Chemical Engineering	Nursing
Chemistry	Pharmacology, Toxicology and Pharmaceutics
Computer Science	Physics and Astronomy
Decision Sciences	Psychology
Earth and Planetary Sciences	Social Sciences
Economics, Econometrics and Finance	Veterinary Sciences
Energy	Dentistry
Engineering	Health Professions
Environmental Science	

[39] such as *Nature* and *Science*

Appendix VIII

Top 50 institutions in AIE research by output and by citations

The top 50 institutions worldwide by publication output and citation count of AIE articles, 2001–2021, are shown in the table below:

Institution name	Country/ region	Scholarly output	Count of citations	Output in top 1% most cited	Output in top 10% most cited	Rank by output	Rank by citations
Hong Kong University of Science and Technology	HKG	1185	95887	162	653	1	1
South China University of Technology	CHN	1052	56780	107	522	2	2
Chinese Academy of Sciences	CHN	755	39792	55	308	3	3
Jilin University	CHN	434	20225	30	186	4	6
Zhejiang University	CHN	381	33549	46	184	5	4
Peking University	CHN	298	15228	23	133	6	7
National University of Singapore	SGP	296	24347	42	198	7	5
Tsinghua University	CHN	283	11135	15	97	8	10
Nanjing University	CHN	212	6354	5	81	9	16
Sun Yat-Sen University	CHN	207	12522	20	95	10	9
University of Chinese Academy of Sciences	CHN	206	7225	9	71	11	12
Shenzhen University	CHN	204	6062	18	111	12	18
Huazhong University of Science and Technology	CHN	203	6967	10	91	13	14
Wuhan University	CHN	181	8573	16	87	14	11
Beijing Institute of Technology	CHN	175	4889	5	56	15	20
East China University of Science and Technology	CHN	169	6543	13	55	16	15
Tianjin University	CHN	163	3950	10	57	17	26
Shandong University	CHN	156	4068	3	44	18	22
Nanchang University	CHN	153	5069	10	43	19	19
Agency for Science, Technology and Research	SGP	146	15026	22	106	20	8
Shanghai Jiao Tong University	CHN	146	7140	16	66	20	13
Centre national de la recherche scientifique (CNRS)	FRA	135	4025	4	32	22	23
Nankai University	CHN	134	6345	22	70	23	17
Soochow University	CHN	132	2624	3	46	24	35
Beijing University of Chemical Technology	CHN	130	3841	6	51	25	27

Beijing Normal University	CHN	107	4025	7	41	26	23
Sichuan University	CHN	106	2560	5	28	27	37
Zhengzhou University	CHN	105	3215	10	48	28	31
Northwest Normal University	CHN	98	1866	3	21	29	47
Anhui University	CHN	97	2673	1	25	30	34
Fudan University	CHN	96	3732	13	45	31	29
University of Science and Technology of China	CHN	85	2323	1	27	32	38
Kyoto University	JPN	84	3981	5	35	33	25
Hangzhou Normal University	CHN	77	4102	6	35	34	21
Nanjing Tech University	CHN	77	2268	4	29	34	39
Southern University of Science and Technology	CHN	77	1825	4	29	34	48
Northeast Normal University	CHN	67	1978	1	23	37	42
The Chinese University of Hong Kong, Shenzhen	CHN	67	383	0	23	37	210
Southern Medical University	CHN	66	1665	2	27	39	54
National Center for Nanoscience and Technology	CHN	64	2785	2	31	40	33
Qingdao University of Science and Technology	CHN	64	1304	1	13	40	69
Southeast University, Nanjing	CHN	64	1161	1	22	40	77
South China Normal University	CHN	59	1610	3	18	43	59
Shanxi University	CHN	59	832	3	22	43	108
Nanjing University of Posts and Telecommunications	CHN	58	1800	1	22	45	49
Birla Institute of Technology and Science Pilani	IND	58	1145	0	10	45	78
Southwest University	CHN	57	1426	2	27	47	64
Dalian University of Technology	CHN	56	1262	1	13	48	70
Central China Normal University	CHN	55	1628	5	22	49	57
China University of Geosciences, Wuhan	CHN	53	1252	4	23	50	72
City University of Hong Kong	HKG	52	1904	6	32	51	46
East China Normal University	CHN	49	1746	3	20	53	50
Nanyang Technological University	SGP	48	3833	7	33	57	28
Seoul National University	KOR	45	3468	4	23	65	30
Flinders University	AUS	40	2587	2	10	79	36
Durham University	GBR	34	1915	3	23	94	45
University of Utah	USA	26	2869	7	22	122	32
University of Virginia	USA	24	1932	2	13	132	43
Universidad Autónoma de Madrid	ESP	16	2061	4	8	201	40
SUNY Buffalo	USA	15	1931	4	7	217	44
Instituto IMDEA Nanociencia	ESP	11	1985	4	7	262	41

Appendix IX

Top 10 institutions by AIE research output for comparator countries and China domestic regions

The top 10 institutions for comparator countries by AIE publication output from 2012–2021 are shown in the table below:

Country	Institution name	Scholarly output	Count of citations	FWCI	Output in top 1% most cited	Output in top 10% most cited	Rank by output
AUS	Flinders University	40	2587	2.2	2	10	1
	University of Melbourne	37	1515	2.1	1	19	2
	Royal Melbourne Institute of Technology University	31	922	1.5	1	5	3
	La Trobe University	30	766	1.8	1	12	4
	Australian National University	13	200	1.4	0	4	5
	Swinburne University of Technology	10	111	1.0	0	1	6
	University of New South Wales	10	138	2.1	0	3	6
	ARC Centre of Excellence in Exciton Science	10	110	1.3	0	2	6
	The Commonwealth Scientific and Industrial Research Organization (CSIRO)	6	104	1.2	0	1	9
	Deakin University	6	129	1.3	0	1	9
	Monash University	6	43	0.8	0	0	9
	University of Technology Sydney	6	36	1.3	0	1	9
CAN	Western University	10	117	1.1	0	2	1
	University of British Columbia	7	279	2.3	0	3	2
	University of Montreal	6	60	0.8	0	0	3
	University of Alberta	6	105	0.9	0	0	3
	University of Calgary	6	178	1.3	0	1	3
	Carleton University	5	306	2.2	0	3	6
	Memorial University of Newfoundland	5	9	0.5	0	0	6
	University of Waterloo	5	175	2.5	0	2	6
	University of Manitoba	4	68	2.0	0	2	9
	University of New Brunswick	4	69	1.1	0	1	9

CHN	Hong Kong University of Science and Technology	1090	67828	3.2	134	590	1
	South China University of Technology	1046	55542	2.9	105	517	2
	Chinese Academy of Sciences	713	27046	2.3	44	281	3
	Jilin University	402	15802	2.4	25	161	4
	Zhejiang University	305	15470	2.7	27	137	5
	Tsinghua University	275	10474	2.1	14	92	6
	Peking University	266	11808	2.5	20	110	7
	Nanjing University	212	6354	2.1	5	81	8
	Shenzhen University	202	5986	2.8	18	110	9
	Huazhong University of Science and Technology	199	6797	2.3	10	90	10
DEU	University of Münster	25	479	1.3	0	6	1
	University of Duisburg-Essen	21	441	1.1	1	2	2
	Heinrich Heine University Düsseldorf	16	226	1.6	0	2	3
	University of Wuppertal	15	395	1.7	0	3	4
	Karlsruhe Institute of Technology	13	265	1.6	0	3	5
	Heidelberg University	13	260	1.7	1	2	5
	Friedrich-Alexander University Erlangen-Nürnberg	7	124	1.5	0	1	7
	Free University of Berlin	6	88	0.8	0	0	8
	University of Würzburg	6	348	2.8	1	4	8
	Federal Institute for Materials Research and Testing Berlin	6	56	0.7	0	0	8
	Max Planck Institute for Polymer Research	6	131	1.4	0	1	8
IND	Birla Institute of Technology and Science Pilani	58	1145	1.3	0	10	1
	Academy of Scientific and Innovative Research	48	796	1.3	0	9	2
	Indian Institute of Technology Guwahati	46	1311	1.5	0	12	3
	Guru Nanak Dev University	40	1111	1.5	0	12	4
	Indian Institute of Science Bangalore	40	1667	2.1	0	19	4
	Indian Association for the Cultivation of Science	35	561	1.1	0	7	6
	Banaras Hindu University	29	327	0.9	0	2	7
	Indian Institute of Technology Indore	29	1120	2.7	2	17	7
	CSIR - Indian Institute of Chemical Technology	25	559	1.1	1	3	9
	University of Calcutta	24	216	1.0	0	3	10
JPN	Kyoto University	75	3049	2.0	4	29	1
	Osaka University	41	962	1.5	2	9	2
	Kyushu University	40	1261	1.7	1	11	3
	Tokyo Institute of Technology	39	1280	1.4	1	9	4
	Hokkaido University	33	1169	1.7	0	14	5

	Kyoto Institute of Technology	26	300	1.0	0	2	6
	The University of Tokyo	26	1220	2.5	1	8	6
	Japan Science and Technology Agency	23	536	1.4	0	6	8
	Tohoku University	20	315	0.9	0	0	9
	Ritsumeikan University	17	229	1.3	0	5	10
KOR	Seoul National University	36	1823	2.6	2	16	1
	Korea University	31	856	2.4	2	15	2
	Konkuk University	21	439	1.4	1	4	3
	Ewha Womans University	17	854	3.1	1	11	4
	Pohang University of Science and Technology	17	597	1.6	0	7	4
	Chonnam National University	16	310	1.1	0	2	6
	Korea Institute of Science and Technology	16	436	1.8	1	7	6
	Sungkyunkwan University	15	373	1.7	0	5	8
	Kyung Hee University	14	273	1.4	1	4	9
	Hanyang University	11	208	1.5	0	3	10
SGP	National University of Singapore	294	24144	3.9	42	197	1
	Agency for Science, Technology and Research	144	14800	4.2	22	104	2
	Nanyang Technological University	46	3423	3.3	6	31	3
	Singapore University of Technology and Design	19	640	2.5	1	9	4
	Singapore National Eye Center	3	258	5.1	0	3	5
	Singapore General Hospital	2	10	1.0	0	0	6
	MOH Holdings Pte Ltd.	2	45	4.9	1	1	6
	National Cancer Centre	1	11	0.9	0	0	8
	National Neuroscience Institute of Singapore	1	4	1.3	0	0	8
	Research and Development Department, Nanofy Technologies Pte. Ltd.	1	10	1.1	0	1	8
UK	Durham University	34	1915	3.0	3	23	1
	Imperial College London	16	497	1.7	0	5	2
	University of Hull	14	313	1.9	2	5	3
	University of Oxford	9	209	1.3	0	2	4
	Loughborough University	7	208	2.5	0	3	5
	University College London	7	130	1.3	0	2	5
	University of Bath	7	503	4.0	3	4	5
	University of Glasgow	7	152	1.2	0	2	5
	Queen Mary University of London	6	181	1.7	1	2	9
	University of Cambridge	6	165	1.7	0	2	9
	Newcastle University	6	137	2.6	0	4	9
USA	University of Utah	25	2730	5.0	7	21	1
	University of Virginia	20	917	2.3	1	9	2
	Massachusetts Institute of Technology	18	1208	2.2	3	4	3

	University of South Florida	17	985	3.4	2	11	4
	University of Iowa	12	202	1.1	0	2	5
	SUNY Buffalo	11	1049	3.9	2	5	6
	University of Texas at Austin	11	299	2.4	1	6	6
	National Institutes of Health	10	615	3.6	1	6	8
	Stanford University	9	537	3.3	1	5	9
	Harvard University	8	72	0.9	0	1	10
	University of California at Los Angeles	8	367	3.0	1	3	10
	University of Houston	8	94	1.4	0	2	10
	University of Illinois at Urbana-Champaign	8	137	0.9	0	1	10

The top 10 institutions for China domestic regions by AIE publication output from 2012–2021 are shown in the table below:

China domestic region	Institution name	Scholarly output	Count of citations	FWCI	Output in top 1% most cited	Output in top 10% most cited	Rank by output
Beijing-Tianjin-Hebei region	Tsinghua University	272	10416	2.1	14	92	1
	University of Chinese Academy of Sciences	174	4768	1.8	6	56	2
	Beijing Institute of Technology	164	4509	1.8	5	53	3
	Tianjin University	159	3902	2.2	10	55	4
	Nankai University	133	6345	3.6	22	70	5
	Beijing University of Chemical Technology	130	3841	2.1	6	51	6
	Peking University	116	4173	2.2	8	47	7
	Beijing Normal University	104	3810	2.2	7	39	8
	Chinese Academy of Sciences	88	2606	2.3	4	38	9
	Shanxi University	59	832	1.8	3	22	10
HKG	The Hong Kong University of Science and Technology	1090	67828	3.2	134	590	1
	The City University of Hong Kong	51	1873	2.9	6	32	2
	The Hong Kong Polytechnic University	47	869	1.6	1	17	3
	The University of Hong Kong	39	1168	2.7	3	17	4
	The Chinese University of Hong Kong	35	1255	2.5	4	17	5
	Hong Kong Baptist University	26	562	1.6	1	6	6
	Tsan Yuk Hospital	1	15	1.3	0	0	7
	AIEgen Biotech Co.,Limited	1	22	1.1	0	0	7
	AUISET Biotechnology Co.,Ltd.	1	14	1.2	0	0	7
	Hong Kong Center for Neurodegenerative Diseases	1	2	0.5	0	0	7
	Guangdong-Hong Kong-Macao Joint Laboratory of Optoelectronic and Magnetic Functional Materials	1	2	0.7	0	0	7

Pearl River Delta region	South China University of Technology	907	50372	2.8	85	437	1
	Hong Kong University of Science and Technology	304	26937	3.6	46	194	2
	Shenzhen University	197	5729	2.8	17	106	3
	Sun Yat-Sen University	186	10099	2.5	17	80	4
	Southern University of Science and Technology	75	1799	2.4	4	27	5
	Southern Medical University	66	1665	2.1	2	27	6
	The Chinese University of Hong Kong, Shenzhen	63	372	1.6	0	23	7
	South China Normal University	57	1516	2.2	3	17	8
	Guangdong University of Technology	45	757	1.5	1	12	9
	Zhejiang Normal University	33	912	1.9	1	13	10
TWN	Chung Yuan Christian University	47	1042	2.0	4	12	1
	National Yang Ming Chiao Tung University	41	889	1.5	0	6	2
	National Sun Yat-sen University	41	941	3.2	6	12	2
	National Taiwan University	38	832	1.8	1	12	4
	Academia Sinica Taiwan	24	726	1.9	0	9	5
	Kaohsiung Medical University	17	575	6.6	6	11	6
	Academia Sinica - Institute of Chemistry	17	531	2.1	0	7	6
	National Taiwan University of Science and Technology	10	149	2.4	1	4	8
	National Tsing Hua University	10	119	1.5	0	2	8
	National Chung Hsing University	9	183	2.2	1	2	10
	Yuan Ze University	9	72	0.7	0	1	10
Yangtze River Delta region	Zhejiang University	290	15138	2.8	26	134	1
	East China University of Science and Technology	162	5240	1.9	10	50	2
	Nanjing University	162	5415	2.2	4	64	2
	Shanghai Jiao Tong University	143	6926	2.8	16	64	4

	Soochow University	128	2578	1.7	3	46	5
	Anhui University	93	2429	1.5	1	23	6
	Fudan University	86	2351	2.4	9	37	7
	University of Science and Technology of China	85	2323	1.8	1	27	8
	Nanjing Tech University	77	2268	2.1	4	29	9
	Hangzhou Normal University	70	3580	2.2	6	30	10

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