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2024 RESEARCH FRONTS

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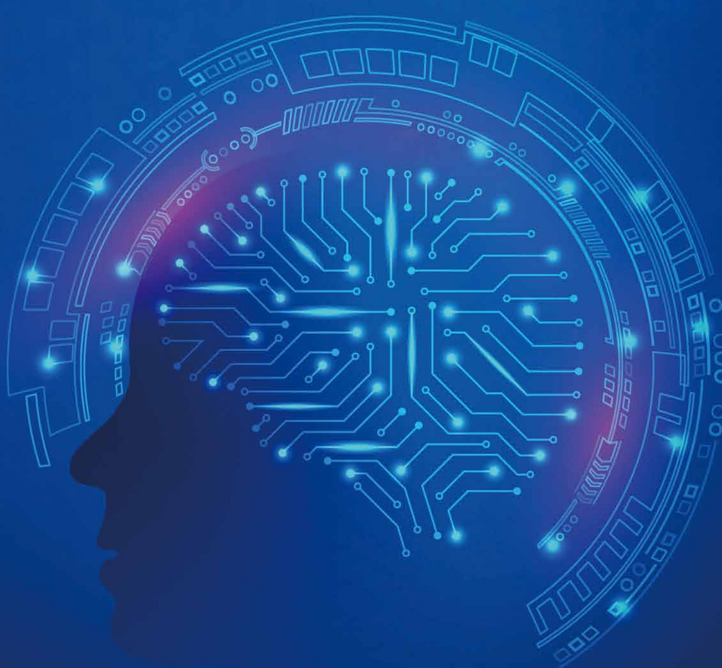


2024 RESEARCH FRONTS

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01

BACKGROUND AND METHODOLOGY

1. BACKGROUND

The world of scientific research presents a sprawling, ever-changing landscape. The ability to identify where the action is and, in particular, to track emerging specialty areas, provides a distinct advantage for administrators, policy makers, and others who need to monitor, support, and advance the conduct of research in the face of finite resources.

To that end, Clarivate generates data and reports on "Research Fronts." These specialties are defined when scientists undertake the fundamental scholarly act of citing one another's work, reflecting a specific commonality in their research – sometimes experimental data, sometimes a method, or perhaps a concept or hypothesis.

By tracking the world's most significant scientific and scholarly literature and the patterns and groupings of how papers are cited – in particular, clusters of papers that are frequently cited together, "Research Fronts" can be discovered. When such a group of highly cited papers attains a certain level of activity and coherence (detected by quantitative analysis), a Research Front is formed, with these highly cited papers serving as the front's foundational "core." Research Front data reveal links among researchers working on related threads of scientific inquiry, even if the researchers' backgrounds might not suggest that they belong to the same "invisible college."

In all, Research Fronts afford a unique vantage point from which to watch science unfold – not relying on the possibly subjective judgments of an indexer or cataloguer, but hinging instead on the cognitive and social connections that scientists themselves forge when citing one another's work. The Research Fronts data provide an ongoing chronicle of how discrete fields of activity emerge, coalesce, grow (or, possibly, shrink and dissipate), and branch off from one another as they self-organize into even newer nodes of activity. Throughout this evolution, the foundations of each core – the main papers, authors, and institutions in each area – can be ascertained and monitored. Meanwhile, analysis of the associated citing papers (those papers that cite the core literature) provides a tool for unveiling the latest progress and the evolving direction of scientific fields.

In 2013, Clarivate published an inaugural report in which 100 hot Research Fronts were identified. In 2014 and 2015, *Research Fronts 2014 and Research Fronts 2015* were undertaken as a collaborative project by the Joint Research Center of Emerging Technology Analysis established by Clarivate and the National Science Library, Chinese Academy of Sciences (CAS). From 2016 to 2023, the Institutes of Science and Development, CAS, National Science Library, CAS, and Clarivate jointly released a succession of annually updated reports of Research Fronts. These reports have gained widespread attention from around the world.

This year, the same methodology with some modifications was employed. For the newest edition, *Research Fronts 2024*, 110 hot Research Fronts and 15 emerging Research Fronts were identified based on co-citation analysis that generated 13318 Research Fronts in the Clarivate database Essential Science Indicators (ESI).

2. METHODOLOGY

The study was conducted in two parts. The process of selecting and naming 125 Research Fronts was completed collaboratively by Clarivate and the Institute of Strategic Information within the Institutes of Science and Development, CAS. Moreover, Clarivate provided data on the core papers and citing papers of the selected 125 Research Fronts. Final selection of key Research Fronts (i.e., hot Research Fronts and emerging Research Fronts), and the interpretation of these respective specialty areas, were completed by the Institute of Strategic Information. For the 2024 update, the Research Fronts drew on ESI data from 2018-2023, which were obtained in March 2024.

2.1 RESEARCH FRONTS SELECTION AND NAMING

Research Fronts 2024 presents a total of 125 Research Fronts, including 110 hot and 15 emerging ones. In 2024, the Research Fronts are classified into 11* broad research areas in the sciences and social sciences. Starting from 13318 Research Fronts in ESI, the objective was to discover which Research Fronts were most active or developing most rapidly.

The specific methodology used for identifying the 125 Research Fronts is described as follows.

2.1.1 SELECTING THE HOT RESEARCH FRONTS

This year, two methods were used for selecting hot Research Fronts. Method 1 continued the selection methods from previous years. Method 2, based on the Research Front selection methods in the fields of mathematics and information in 2022, was further improved in 2023 and applied in 2024.

Method 1: Research Fronts in each ESI field were first ranked by total citations, and the Top 10% of the fronts in each ESI field were extracted. These Research Fronts were then merged into 11 broad areas and re-ranked according to the average (mean) year of their core papers to produce the "youngest" ones in each broad area. Based on these data, the strategic information professionals with domain knowledge adjusted and merged some Research Fronts. Through the aforementioned steps, several hot Research Fronts were selected in 11 broader areas.
Method 2: Research Fronts were ranked based on their average citations per core paper, and those above the mean calculated independently in each of the 11 broader areas were selected. Then, re-ranked them according to mean publication years of their core papers. The strategic information professionals assess whether the candidate fronts have accelerated the advancements of knowledge in each area and make the selection. By combining the two methods mentioned above, a total of 110 hot Research Fronts were selected, with 10 in each of the 11 broader areas. The 10 fronts selected for each of the 11 highly aggregated main areas of science and social sciences represent the hottest of the largest fronts, not necessarily the hottest Research Fronts across the database (all disciplines). Due to the different characteristics and citation behaviors in various disciplines, some fronts are much smaller than others in terms of number of core and citing papers.

2.1.2 SELECTING THE EMERGING RESEARCH FRONTS

A Research Front with core papers of recent vintage indicates a specialty with a young foundation that is rapidly growing. To identify emerging specialties, the immediacy of the core papers is a priority, and that is why it is characterized as "emerging." For the 11 broader areas, to identify emerging specialties, extra preference, or weight, was given to the currency of the foundation literature: only Research Fronts whose core papers dated, on average, to the second half of 2022 or more recently were considered. Then these were sorted in descending order by their total citations in each ESI field corresponding to the 11 broader areas. The top 10% Research Fronts were selected and delivered to the Institute of Strategic Information, where information professionals with domain knowledge made the

* 11 broader areas include "Agricultural, plant and animal sciences", "Ecology and environmental sciences", "Geosciences", "Clinical medicine", "Biological sciences", "Chemistry and materials science", "Physics", "Astronomy and astrophysics", "Mathematics", "Information science", and "Economics, psychology and other social sciences".

final selection of emerging Research Fronts and grouped them into 11 broader fields. Fifteen fronts were selected as emerging for the 11 broader areas. Because the selection was not limited to any research area, the 15 fronts are distributed unevenly in the 11 fields. For example, there is no emerging Research Front in Mathematics, while there are four emerging Research Fronts in "Clinical medicine".

Based on the above two methods, the report presents the Top 10 hot fronts in each of the 11 broad areas (110 fronts in total) and 15 emerging ones.

2.1.3. NAMING THE RESEARCH FRONTS

Based on the research themes, main contents, and characteristics of the selected Research Fronts, the strategic information professionals re-named each of the 125 Research Fronts and made some adjustments after consulting the domain experts.

2.2 FINAL SELECTION AND INTERPRETATION OF KEY RESEARCH FRONTS

Based on the core papers and citing papers of 125 Research Fronts provided by Clarivate, information professionals at the Institute of Strategic Information, conducted a detailed analysis and interpretation to highlight 28 key Research Fronts (Chapter 2 to Chapter 12) of particular interest, including both hot and emerging fronts.

As discussed above, a Research Front consists of a core of highly cited papers along with the citing papers that have frequently co-cited the core. In other words, core papers are all highly cited papers in ESI – papers that rank in the top 1% in terms of citations in the same ESI field and in the same publication year. Since the authors, institutions and countries/regions listed on the core papers have made significant contributions to the particular specialty, a tabulation of these appears in the analysis of the Research Fronts. Meanwhile, by reading the full text of the citing articles, greater precision can be obtained in specifying the topic of the Research Front, especially in terms of its recent development or leading-edge findings. In this case, it is not necessary that the citing papers are themselves highly cited.

2.2.1 FINAL SELECTION OF KEY RESEARCH FRONTS

In Research Fronts 2014, an index known as CPT was designed to select key Research Fronts. From 2015 on, a scale indicator, the number of core papers (P), has also been considered.

(1) The number of core papers (P)

ESI classifies Research Fronts according to the co-cited paper clusters and reveals their development trend based on the metadata of the paper clusters, along with statistical analysis. The number of core papers (P) indicates the size of a Research Front, and average (mean) publication year and the time distribution of the core papers demonstrates the progress of the area. The number of core papers (P) also illustrates the importance of the knowledge base in the Research Fronts. In a certain period of time, a higher P value usually represents a more active Research Front.

(2) CPT indicator

The CPT indicator was applied to identify the key Research Fronts. C represents the number of citing articles, i.e., the tally of articles citing the core papers; P is the number of core papers; T indicates the age of citing articles, which is the number of citing years, from the earliest year of a citing paper to the latest one. For example, if the most-recent citing paper was published in 2022 and the earliest citing paper was published in 2018, the age of citing articles (T) equals 5.

$$CPT = (C / P) / T = \frac{C}{P \cdot T}$$

CPT is the ratio of the average citation impact of a Research Front to the age/occurrence of its citing papers, meaning the higher the number, the hotter or the more impactful the topic. It measures how extensive and immediate a Research Front is and can be used to explore the emerging or developing aspects of Research Fronts and to forecast future possibilities. The degree of citation influence can be seen from the amount of citing papers, while it also takes the publication years of citing papers into account and demonstrates the trend and extent of attention on certain Research Fronts across years.

Given the condition that a particular Research Front was cited continuously,

1) When P as well as T is equal in two Research Fronts, the higher C is, the higher CPT will be, indicating the broader citation influence of the Research Front with higher C.

2) When C as well as P is equal in two Research Fronts, the lower T, the higher CPT, indicating the Research Front with lower T attracts more intensive attention in a short period.

3) When C as well as T is equal in two Research Fronts, the lower P, the higher CPT, indicating the broader citation influence of the Research Front with lower P.

In the *Research Fronts 2024,* for each of the 11 broad research areas, one key hot Research Front was selected based on the number of core papers (P) in combination with the professional judgment of analysts from the Institute of Strategic Information. Another key hot Research Front was chosen by the indicator CPT. Based on their knowledge, the analysts assessed the significance of the key hot Research Fronts in addressing major issues in the given area. Firstly, the Research Front with the greatest number of core papers (P) in a broad research area was selected. If the front with the greatest P had been interpreted in previous years and there was no significant change of the core papers, then the Research Front with the second highest P would be selected as the key hot Research Front, and so on. Furthermore, another key hot front was selected based on the integration of CPT and professional judgement.

By taking advantage of the above two indicators as well as our domain experts' judgment, we selected 22 key hot Research Fronts from the 110 hot Research Fronts in the 11 broad research areas. Moreover, based on CPT and experts' judgment, six key emerging Research Fronts were selected from the emerging Research Fronts. Thus, we interpret in detail the selected 28 key Research Fronts from the 125 Research Fronts.

2.2.2 ANALYSIS AND INTEPRETATION OF KEY RESEARCH FRONTS

Based on the data of the selected 125 Research Fronts, the development trends of the 110 hot Research Fronts in the 11 broad areas were analyzed, and the research themes of the emerging Research Fronts were revealed and researched. The 28 key Research Fronts were subsequently examined in greater detail.

(1) Examination of key hot Research Fronts

In each broad area, the development trends of the Top 10 hot Research Fronts, including the important research directions, distribution characteristics, and evolving trends of Research Fronts, were analyzed based on the number of core papers, times cited, mean publication year of core papers, and the annual change of the citing paper distribution.

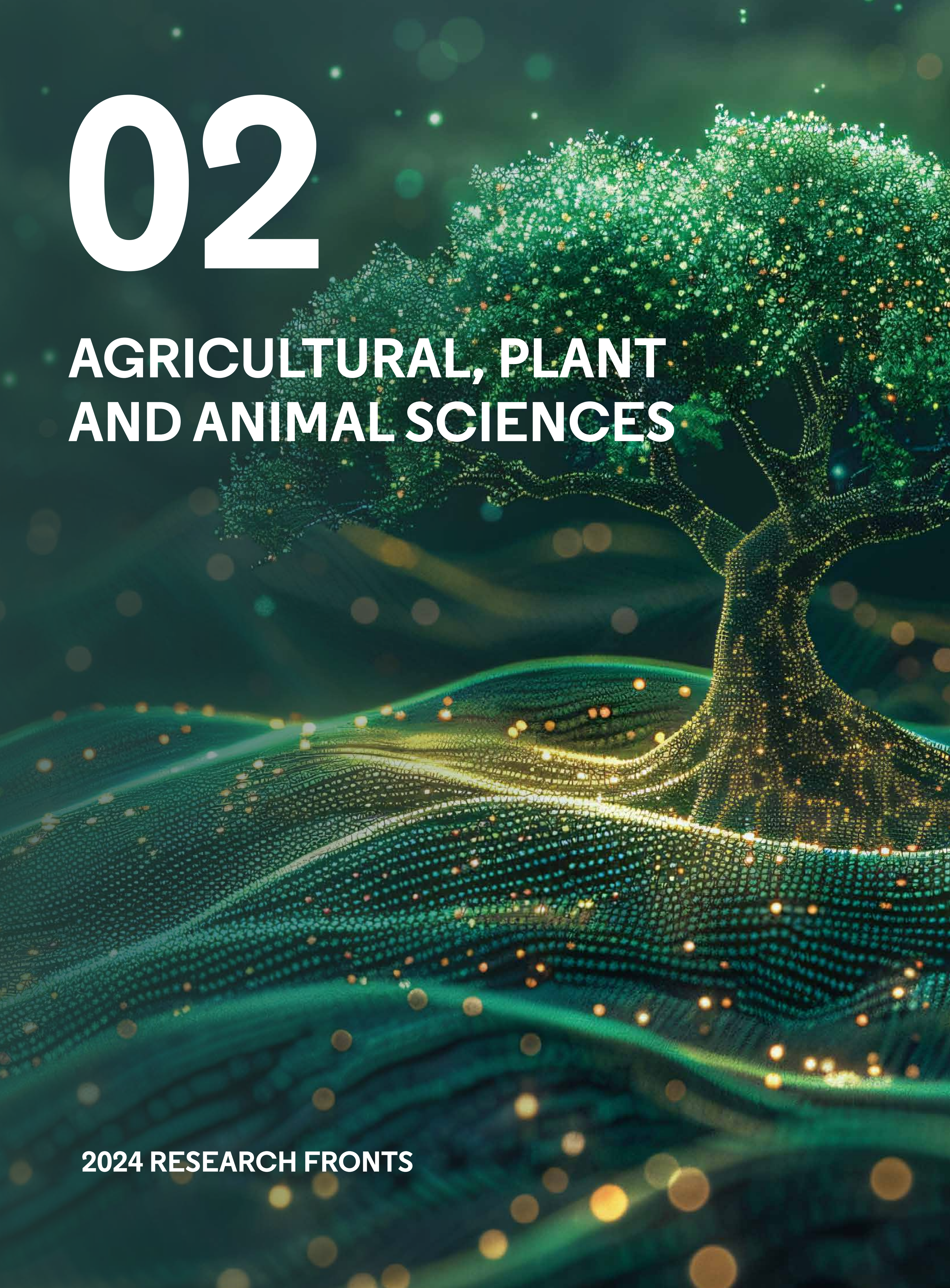
The first table under each discipline section lists the 10 top ranked Research Fronts for each of the 11 broad areas, as well as the number of core papers, total citations, and the average publication year of the core papers of each Research Front. A bubble diagram shows the age distribution of the citing articles in the 10 Research Fronts listed for each broad area. The size of the bubble represents the quantity of citing articles per year. Key hot Research Fronts can be easily identified, particularly when large amounts of citing papers appear in a very short publication window (i.e., the first two explanations for CPT's values, as discussed above). But other data must be considered when the number of core papers is small. Generally speaking, the number of citing papers in most fronts will grow with time, so the bubble diagram can also help us understand the development of the Research Fronts.

For the two key hot Research Fronts selected in each broad area, their concepts and connotations, development contexts, layout of research force were further analyzed and interpreted, and the research content, value, and impact of the top cited core papers were revealed.

The first table for each key hot Research Front statistically analyzes the affiliated countries/regions and institutions represented in the core papers and summarizes their active status, thereby revealing the players making fundamental contributions in the key hot Research Front. Countries/regions and institutions of the citing papers in a key hot Research Front are analyzed in the second table to reveal their research strategy as they carry forward the work in these specialty areas.

(2) Interpretation of key emerging Research Fronts

Because the emerging Research Fronts identified were usually small in terms of number of core and citing papers, the figures did not generally lend themselves to detailed statistical analysis. Nevertheless, information professionals endeavored to examine and interpret the research topics to better understand the fundamental concepts, the current research breakthroughs, and future development prospects in the key emerging Research Fronts.



02

AGRICULTURAL, PLANT AND ANIMAL SCIENCES

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN AGRICULTURAL, PLANT AND ANIMAL SCIENCES

The Top 10 hot Research Fronts in agricultural, plant and animal sciences mainly involve four subfields: plant gene regulation; animal nutrition; food science and engineering; and forest ecological monitoring (Table 1, Figure 1). The subfield of plant gene regulation accounts for five hot Research Fronts, pertaining respectively to plant gaseous hormone ethylene; microbial inoculation; single-cell transcriptome sequencing; plant NLR immune receptors; and RNA N6-methyladenosine modification in plants.

Three hot Research Fronts concern the subfield of food science and engineering, focusing on three key research directions: food pollution detection, food nutrients, and food fermentation engineering. The main areas of focus include surface-enhanced Raman scattering (SERS) detection methods, plant polysaccharides, and the microbial metabolic networks involved in the formation of flavor in Chinese liquor. The subfields of animal nutrition and forest ecological monitoring each account for one front, centering on the feed additive of biological nanoparticles and the application of deep learning in forest monitoring, respectively.

Over the past 11 years of the Research Fronts survey, the subfields of plant gene regulation, food science and engineering, and animal nutrition have consistently been hotspots, with key research topics emerging in these areas year after year. Notably, the Research Fronts in the subfield of plant gene regulation mainly focus on growth and development regulation and immune regulation, among which the plant immune mechanism mediated by NLR immune receptors have continuously appeared in Research Front roundups for the past four years. Similarly, both the development of feed additives in the subfield of animal nutrition, and food pollutant detection and nutrient analysis the subfield of food science and engineering, have been selected in the list multiple times. Meanwhile, a new hot front on RNA modification regulation enters the Top 10 list for the first time.

Table 1: Top10 Research Fronts in agricultural, plant and animal sciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Effect of microbial inoculation on plant growth and stress resistance	39	1217	2022.4
2	Effect of dietary supplementation of biological nanoparticles on animal growth and health	25	1512	2021.3
3	The biosynthesis, signaling, and roles of the plant hormone ethylene	13	1129	2021.3
4	Structural characterization, antioxidant activity, and disease treatment effects of plant polysaccharides	11	1175	2021.2
5	The disease resistance mechanism of plant NLR immune receptor	47	5736	2021.0
6	Application of surface-enhanced Raman scattering in food contaminant detection	19	1591	2020.9
7	Detection, regulation and function of RNA N6-methyladenosine modification in plant	33	3182	2020.8
8	Microbial metabolic network of flavor development during Baijiu fermentation process	13	1213	2020.8
9	Application of convolutional neural network and high-resolution unmanned aerial vehicle images in individual tree detection and tree species classification	18	1818	2020.7
10	Application of single-cell transcriptome sequencing in studying plant tissue development	28	2477	2020.6

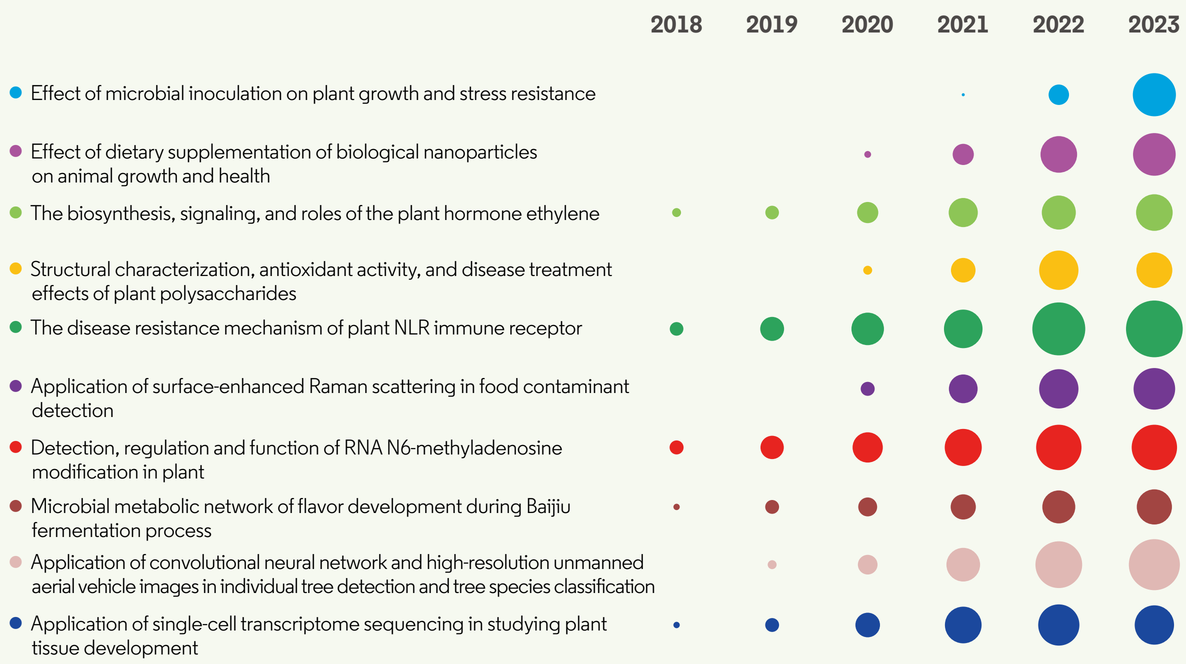


Figure 1: Citing papers for the Top 10 Research Fronts in agricultural, plant and animal sciences

1.2 KEY HOT RESEARCH FRONT – "Detection, regulation and function of RNA N6-methyladenosine modification in plant"

RNA methyladenosine modification refers to the chemical modification in which methyladenine of RNA is selectively combined with methyl groups, under the catalysis of methyltransferase. N6 methyladenosine (m6A) methylation is one of the most critical internal modifications of RNA, which occurs at the sixth N position of RNA adenylate (A) and is the most abundant epigenetic transcriptomic modification in eukaryotic mRNA. M6A methylation is a conserved post-transcriptional mechanism used to enrich and regulate genetic information in eukaryotes.

The scope and function of this modification in plants has always been a research hotspot, especially in model plant systems. Three key proteins involved in the m6A methylation of plants include methyltransferases (writers), demethylases (erasers), and binding proteins (readers). The characterization and functional analysis of these three proteins are currently the most active hotspots in plant biology research. In the foreseeable future, functional analysis of m6A in plants will flourish and contribute to crop genetic improvement through manipulation of the epigenetic transcriptome.

Thirty-three core papers anchor this hot Research Front, focusing on research into the three key proteins mentioned above. These studies involve both theoretical exploration and technological development. The fundamental theory research delves into the composition and evolution of m6A methylation regulation mechanisms in plants, as well as the functions of m6A modification, including its effects on stress resistance, fruit development, and yield. Technological development in this area centers on an innovative approach to detect RNA methylation modification: nanopore direct RNA-sequencing, which is also used in the complexity analysis of mRNA processing and m6A modification.

Among the 33 core papers, the most frequently cited paper has attracted nearly 500 citations at this writing (Figure 2). Published in *Nature Methods* in 2018 by Oxford Nanopore Technologies Ltd., a British DNA sequencing company, this paper introduced a nanopore direct RNA-sequencing method. As an important technology for investigating RNA methylation modification, it is a highly parallel, real-time, and single-molecule approach that enables the direct sequencing of RNA molecules and the detection of nucleotide analogues in RNA without reverse transcription or PCR amplification steps.

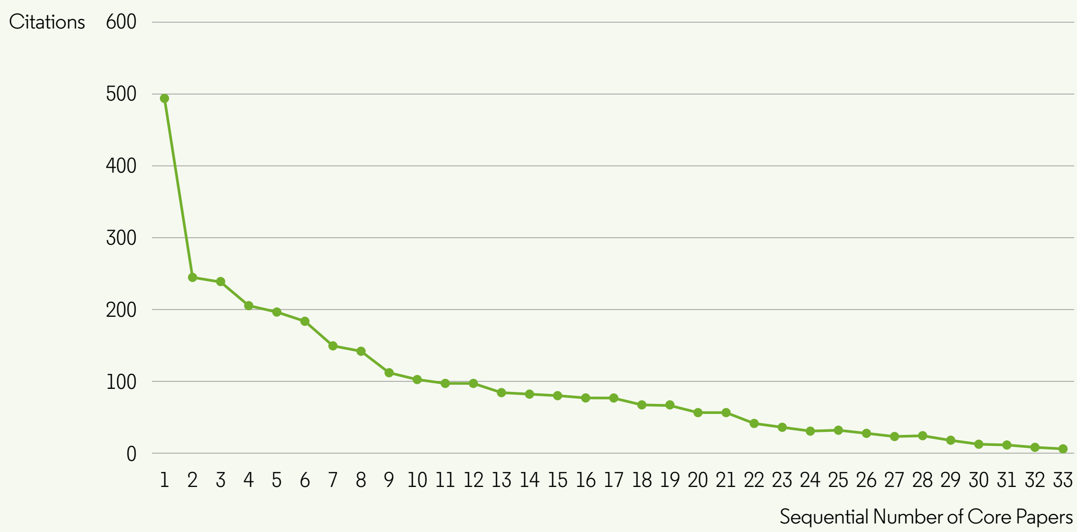


Figure 2: Citation frequency distribution curve of core papers in the Research Front "Detection, regulation and function of RNA N6-methyladenosine modification in plant"

Among the top countries and institutions producing core papers (Table 2), China leads with 22 papers, representing 67% of the total, followed by the USA with 11 papers. Meanwhile, the other listed nations have contributed fewer than five papers each, far below the output of China and the USA. Among the prolific contributing institutions, Peking University ranks 1st, with the University of Chicago and Howard Hughes Medical Institute sharing second place, and the Chinese Academy of Sciences in 3rd.

Table 2: Top countries and institutions producing core papers in the Research Front "Detection, regulation and function of RNA N-6-methyladenosine modification in plant"

Country Ranking	Country	Core Papers	Proportion
1	China	22	66.7%
2	USA	11	33.3%
3	UK	4	12.1%
4	Denmark	3	9.1%
5	Germany	2	6.1%
5	Israel	2	6.1%
5	Australia	2	6.1%
5	South Korea	2	6.1%
5	Singapore	2	6.1%

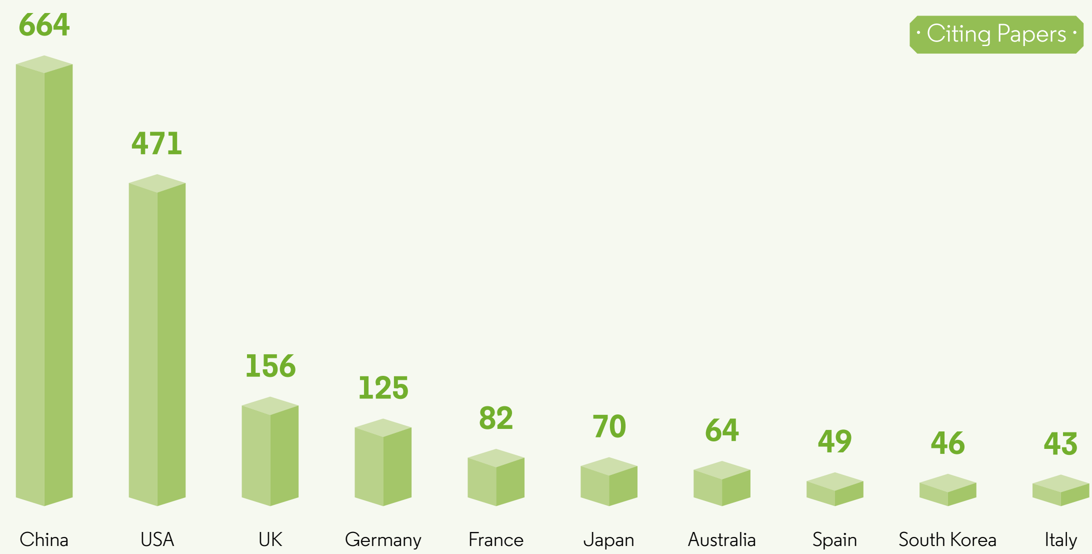
Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Peking University	China	7	21.2%
2	University of Chicago	USA	5	15.2%
2	Howard Hughes Medical Institute	USA	5	15.2%
4	Chinese Academy of Sciences	China	4	12.1%
5	Northwest A&F University	China	3	9.1%
5	University of Copenhagen	Denmark	3	9.1%
7	Weizmann Institute of Science	Israel	2	6.1%
7	Chonnam National University	South Korea	2	6.1%
7	University of New South Wales	Australia	2	6.1%
7	Shandong Agricultural University	China	2	6.1%
7	University of Liverpool	UK	2	6.1%
7	National University of Singapore	Singapore	2	6.1%
7	Nankai University	China	2	6.1%
7	Cornell University	USA	2	6.1%
7	Tsinghua University	China	2	6.1%
7	Chinese Academy of Agricultural Sciences	China	2	6.1%
7	Jiangsu Normal University	China	2	6.1%

In terms of citing papers (Table 3), China and the USA remain the top contributors, significantly ahead of other countries, indicating their strong focus and ongoing research interest in this area. The UK and Germany are actively following suit, forming the second tier in terms of citing-paper output. Among the top citing institutions, the Chinese Academy of Sciences has contributed 89 papers, leading other institutions, followed by the National Center for Scientific Research of France, which contributed 71 citing papers, ranking 2nd. Peking University in China and the University of Chicago in the USA, which performed notably in their numbers of core papers, also register strongly in terms of follow-up research in this area, ranking 4th and 5th, respectively.

Table 3: Top countries and institutions producing citing papers in the Research Front "Detection, regulation and function of RNA N6-methyladenosine modification in plant"

Country Ranking	Country	Citing Papers	Proportion
1	China	664	41.9%
2	USA	471	29.7%
3	UK	156	9.8%
4	Germany	125	7.9%
5	France	82	5.2%
6	Japan	70	4.4%
7	Australia	64	4.0%
8	Spain	49	3.1%
9	South Korea	46	2.9%
10	Italy	45	2.8%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	89	5.6%
2	National Center for Scientific Research of France (CNRS)	France	71	4.5%
3	Chinese Academy of Agricultural Sciences	China	51	3.2%
4	Peking University	China	41	2.6%
5	University of Chicago	USA	36	2.3%
6	National Institute of Health and Medical Research (INSERM)	France	34	2.1%
6	Sun Yat Sen University	China	34	2.1%
6	University of Pennsylvania	USA	34	2.1%
9	Howard Hughes Medical Institute	USA	32	2.0%
10	Zhejiang University	China	31	2.0%



1.3 KEY HOT RESEARCH FRONT – "Application of single-cell transcriptome sequencing in studying plant tissue development"

Single-cell transcriptome sequencing, also known as single-cell RNA sequencing (scRNA-seq), is a new disruptive sequencing technology for transcriptomes at the single-cell level. It is a powerful tool for studying gene expression within individual cells and can solve the problems of small samples or cell heterogeneity in research fields such as early embryonic development, stem cells, cancer, and immunity.

The technology makes it possible to analyze the behavior and mechanisms of individual cells, along with the relationship between individual cells and the organism. The advent of scRNA-seq is revolutionizing the details of whole-transcriptome snapshots from a tissue to a cell, and, since its emergence, it has developed rapidly.

In 2009, a team under Tang Fuchou at Peking University completed the world's first high-throughput sequencing of single-cell RNA; In 2011, a group led by Nicholas Navin, then at Cold Spring Harbor Laboratory in the USA, completed the world's first single-cell DNA sequencing; In 2013, the team of Xiaoliang Xie at Peking University invented MALBAC amplification technology; In 2014, the American company Fluidigm released its first fully automated single-cell preparation system; In 2015, Steven A. McCarroll at the Harvard Medical School led the launch of Drop Seq technology based on droplet encapsulation of single cells and capture of magnetic beads, while Stephen Fodor, at the company Cellular Research in the USA, and colleagues introduced microwell technology based on microplates; In 2016, 10x Genomics, an American company, launched the commercial single-cell analysis system Chromium; In 2017, BD Corporation in the USA released the single-cell analysis system Rhapsody, and the Human Cell Atlas was launched; In 2018, single-cell sequencing was named one of the top ten scientific breakthroughs by *Science*; In 2019, single-cell sequencing was named the annual technology of life sciences by *Nature*. With the continuous technological breakthroughs and the ongoing introduction of new analytical systems, the fields using applications of scRNA-seq have expanded from biomedicine to botany.

Twenty-eight core papers underlie this hot Research Front, focusing on the application of single-cell transcriptome sequencing technology in research on tissue development in plants, such as Arabidopsis, rice, corn, tea, poplar. This includes the development of roots, inflorescence meristematic tissues, leaf mesophyll, and stem secondary vascular tissues.

Among those 28 core papers, the two most-cited papers have both attracted 204 citations at this writing (Figure 3). One was published in *Molecular Plant* in 2019 by the Center for Excellence in Molecular Plant Sciences (Institute of Plant Physiology and Ecology) of the Chinese Academy of Sciences, using single-cell transcriptome sequencing to reveal the high heterogeneity of Arabidopsis root cells and recognize the expression characteristics of intermediate states during root cell differentiation. The other high-impact core paper was published in *Plant Physiology* in 2019 by researchers at the University of Michigan in the USA, using single-cell transcriptome sequencing to analyze the molecular relationships between individual plant cells and to provide a gene expression profile for the first generation of Arabidopsis roots.

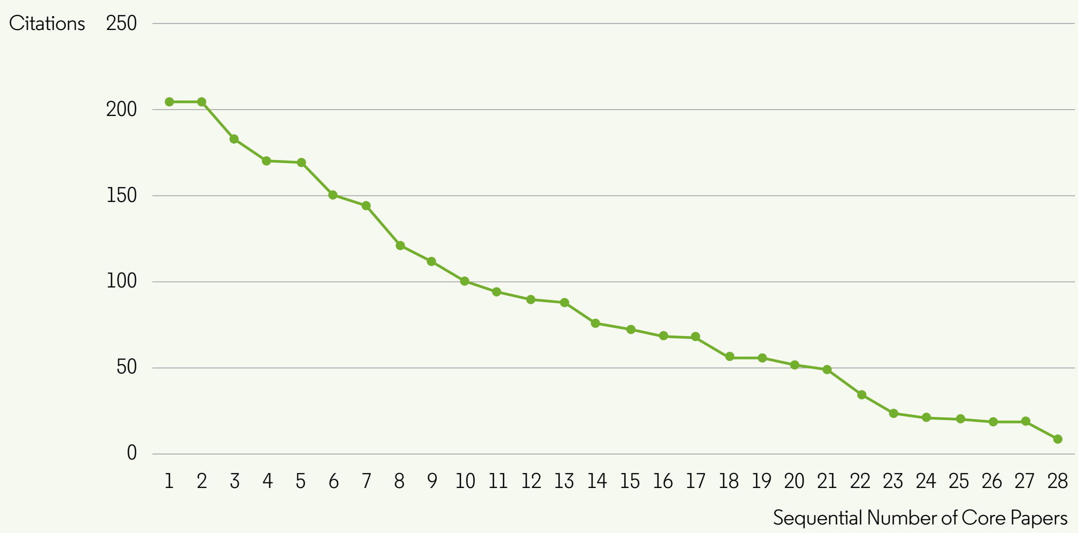


Figure 3: Citation frequency distribution curve of core papers in the Research Front "Application of single-cell transcriptome sequencing in studying plant tissue development"

Among the top countries and institutions producing core papers (Table 4), the USA fields the highest contribution, with 15 papers. China follows closely, contributing 11 papers. Germany ranks 3rd. Among the prolific contributing institutions, the Chinese Academy of Sciences, the University of Georgia, and the University of Washington in the USA stand side by side, ranking 1st. This reflects that both the USA and China attach great importance to research on single-cell transcriptome sequencing methods and their applications in the plant field.

Table 4: Top countries and institutions producing core papers in the Research Front "Application of single-cell transcriptome sequencing in studying plant tissue development"

Country Ranking	Country	Core Papers	Proportion
1	USA	15	53.6%
2	China	11	39.3%
3	Germany	6	21.4%
4	Japan	3	10.7%
4	Belgium	3	10.7%
6	UK	2	7.1%
6	Switzerland	2	7.1%
6	Netherlands	2	7.1%
9	Finland	1	3.6%
9	Israel	1	3.6%
9	Singapore	1	3.6%
9	Australia	1	3.6%

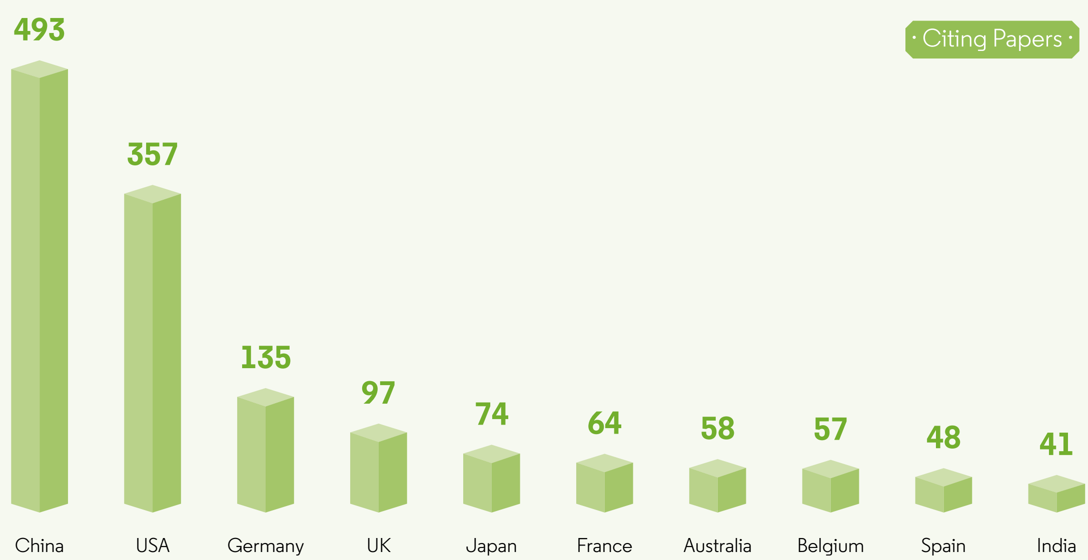
Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Chinese Academy of Sciences	China	4	14.3%
1	University of Georgia	USA	4	14.3%
1	University of Washington	USA	4	14.3%
4	Ghent University	Belgium	3	10.7%
5	Nagoya University	Japan	2	7.1%
5	Henan University	China	2	7.1%
5	Shanghai Normal University	China	2	7.1%
5	Heinrich Heine University Dusseldorf	Germany	2	7.1%
5	Technical University of Munich	Germany	2	7.1%
5	University of Michigan	USA	2	7.1%
5	Rutgers State University	USA	2	7.1%
5	University of Geneva	Switzerland	2	7.1%
5	Emory University	USA	2	7.1%
5	Shanghai Jiao Tong University	China	2	7.1%
5	ShanghaiTech University	China	2	7.1%
5	Zhejiang University	China	2	7.1%

In terms of countries and institutions that cite the core papers in this hot front (Table 5), China and the USA rank 1st and 2nd, accounting for 41.5% and 30.0% respectively, far surpassing other countries. Notably, while China is ranked 2nd in terms of the production of core papers, it secures the top spot in the number of citing papers, surpassing that of the USA by over 100. In terms of citing institutions, Chinese entities demonstrate remarkable prominence. The Chinese Academy of Sciences and the Chinese Academy of Agricultural Sciences rank 1st and 2nd with 92 and 58 citing papers, respectively. Tied for third place are Huazhong Agricultural University and Ghent University in Belgium. Three institutions in the USA enter the Top 10 list, ranking 6th, 8th and 10th, respectively.

Table 5: Top countries and institutions producing citing papers in the Research Front "Application of single-cell transcriptome sequencing in studying plant tissue development"

Country Ranking	Country	Citing Papers	Proportion
1	China	493	41.5%
2	USA	357	30.0%
3	Germany	135	11.4%
4	UK	97	8.2%
5	Japan	74	6.2%
6	France	64	5.4%
7	Australia	58	4.9%
8	Belgium	57	4.8%
9	Spain	48	4.0%
10	India	41	3.4%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	92	7.7%
2	Chinese Academy of Agricultural Sciences	China	58	4.9%
3	Ghent University	Belgium	49	4.1%
3	Huazhong Agricultural University	China	49	4.1%
5	National Research Institute for Agriculture, Food and Environment	France	47	4.0%
6	Max Planck Society	Germany	42	3.5%
6	United States Department of Agriculture (USDA)	USA	42	3.5%
8	National Center for Scientific Research of France (CNRS)	France	41	3.4%
8	University of Georgia	USA	41	3.4%
10	University of California Davis	USA	40	3.4%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN AGRICULTURAL, PLANT AND ANIMAL SCIENCES

In the area of agricultural, plant and animal sciences, two emerging Research Fronts have been identified: "Application of biopolymer film in food preservation packaging" and "Application of deep transfer learning in crop classification and disease detection" (Table 6).

Table 6: Emerging Research Fronts in agricultural, plant and animal sciences

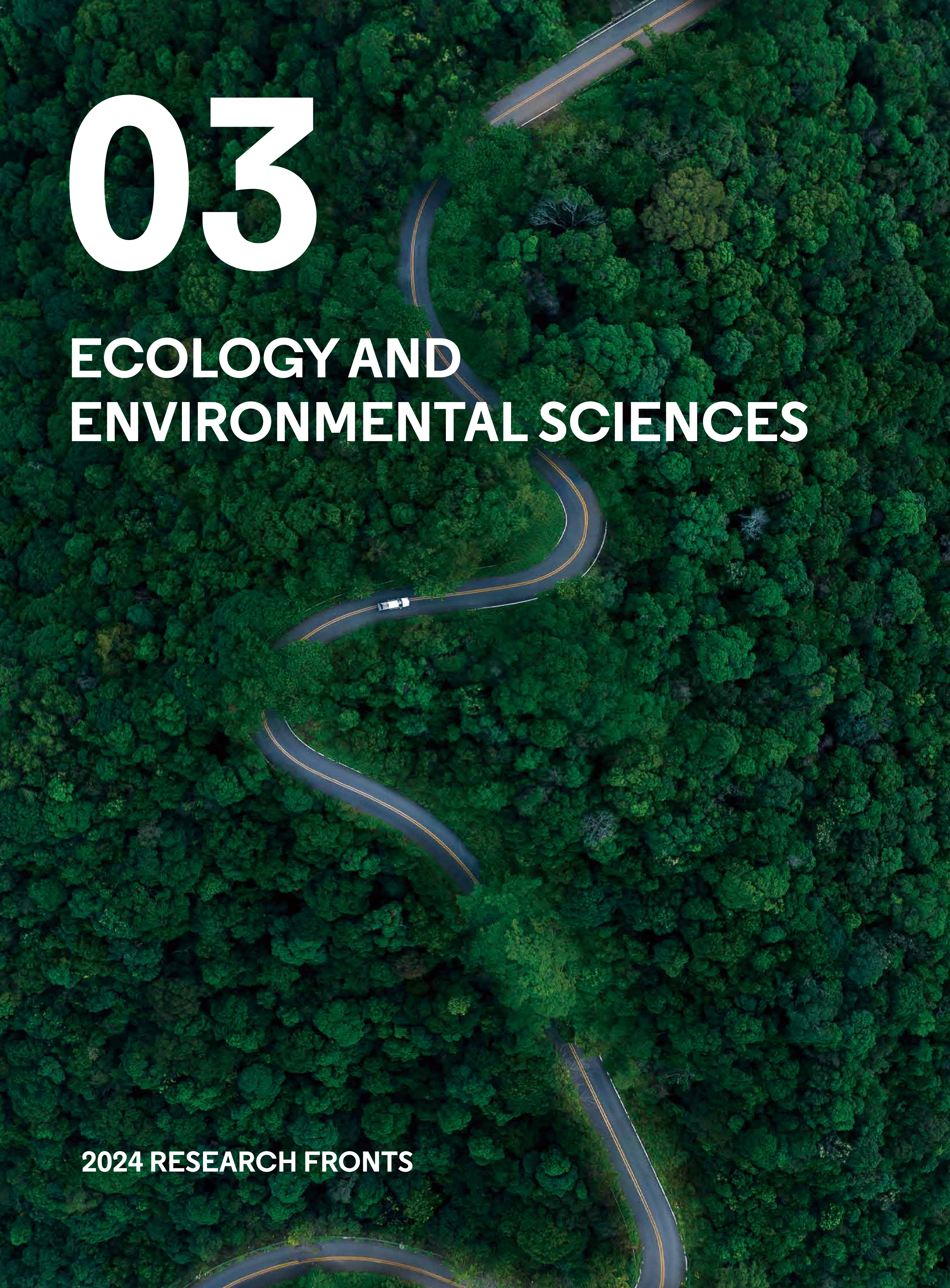
Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core papers
1	Application of deep transfer learning in crop classification and disease detection	5	150	2023.0
2	Application of biopolymer film in food preservation packaging	9	186	2022.9

2.2 KEY EMERGING RESEARCH FRONT – "Application of deep transfer learning in crop classification and disease detection"

Deep Transfer Learning is a specific deep-learning method aimed at improving the learning efficiency and performance of target tasks by transferring knowledge learned from one domain (source domain) to another domain (target domain), a technique particularly suitable for situations in which data in the target domain is scarce or difficult to annotate. Deep transfer learning has been widely applied across multiple fields, including image classification, object detection and segmentation, and style transfer in computer vision; sentiment analysis, machine translation, and text generation in natural language processing; and speech-to-text and sentiment recognition in speech recognition; as well as medical imaging analysis and genomic data analysis in medicine and bioinformatics.

Compared to deep learning, which typically trains on a large amount of labeled data, deep transfer learning can solve the problem of insufficient training data. For example, in some fields such as bioinformatics and robotics, due to the high cost of data collection and labeling, it is very difficult to build large-scale, well-annotated datasets, making it difficult for deep learning to be effective. Transfer learning, on the other hand, relaxes the assumption that training data must be independently and identically distributed from test data, which is an important assumption in the field of machine learning, known as the independent identically distribution assumption.

This emerging front has primarily focused on the following three areas of the research: using transfer learning to develop deep learning models (such as CNN), with findings showing that transfer learning can improve fruit classification ability; developing models through transfer learning to classify fruit ripeness and identify fruit types; comparing and analyzing different deep learning models used for crop disease classification, and confirming the effectiveness of deep learning models in classifying crop diseases.



03

ECOLOGY AND ENVIRONMENTAL SCIENCES

2024 RESEARCH FRONTS

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN ECOLOGY AND ENVIRONMENTAL SCIENCES

The Top 10 hot Research Front in ecology and environmental sciences are mainly distributed in two sub-areas: ecological sciences and environmental sciences (Table 7 and Figure 4).

The hot Research Fronts in the environmental-science subfield mainly focus on emerging pollutants as well as the elimination of pollutants in general, climate change, and environmental epidemiology. Research on microplastic pollution has been a hot topic in environmental sciences over the past decade and has repeatedly emerged as an important concentration of activity in the Research Front reports. Related topics have been selected as Top 10 hot Research Fronts and emerging Research Fronts multiple times in 2015 to 2017, 2020 to 2023.

In 2024, two hot fronts focus on microplastics, including "Detection and quantitative analysis of microplastics in human tissue" and "Environmental fate and ecotoxicity of tire wear particles". "Detection and quantitative analysis of microplastics in human tissue" was selected as an Emerging Research Front in 2023. Tire-wear particles are one of the main sources of microplastics in the environment and are also a newly recognized emerging pollutant. A recent study in the UK has shown that particulate pollution from car-tire wear is nearly 2,000 times greater than that from exhaust emissions.

In addition, carbon sequestration technology for addressing climate change is currently a highly regarded technology in the field of environmental science. Two related hot fronts pertain this year: "Highly efficient catalytic synthesis of urea from carbon dioxide and nitrogen" and "Techno-economic assessment of CO_2 direct air capture". The latter has been selected as a hot front for the second consecutive year.

Meanwhile, the hot front related to pollutant elimination is "Activator and mechanism of peroxymonosulfate for pollutants degradation", while the fronts related to the use of persulfate activation oxidation for eliminating pollutants have been selected as Top 10 hot Research Fronts multiple times in 2017 to 2018 and 2022 to 2023. Polyhydroxyalkanoates (PHAs) are polyesters synthesized by microorganisms. Due to their excellent properties such as biodegradability, biocompatibility, and optical characteristics, they have become widely recognized bioplastics in both scientific and industrial communities. The related hot Research Front is "Production, applications and biodegradability of Polyhydroxyalkanoate bioplastics".

Two hot Research Fronts derive from advances in environmental epidemiology: "Detection of SARS-CoV-2 in wastewater and COVID-19 epidemiological surveillance based on wastewater," which has been selected as a hot front for three consecutive years, and "The relationship between zoonotic diseases and ecological and environmental problems caused by human activities and related risks", which examines the relationship between environmental problems and epidemic diseases.

The hot Research Fronts in the ecological-science subfield mainly emphasize biodiversity research and protection, as examined in two fronts: "The status of insect declines, driving factors and solutions" and "Application of population genomics in wildlife conservation and management". Among these two fronts, "The status of insect declines, driving factors and solutions" has now been listed as a hot front for the fourth consecutive year, demonstrating that biodiversity conservation has become a global focal point of concern.

Table 7: Top 10 Research Fronts in ecology and environmental sciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Environmental fate and ecotoxicity of tire wear particles	18	1649	2021.7
2	Highly efficient catalytic synthesis of urea from carbon dioxide and nitrogen	18	1641	2021.6
3	Detection and quantitative analysis of microplastics in human tissue	4	2508	2021.0
4	Activator and mechanism of peroxymonosulfate for pollutants degradation	26	5266	2020.9
5	Production, applications and biodegradability of Polyhydroxyalkanoate bioplastics	18	2189	2020.7
6	Application of population genomics in wildlife conservation and management	21	2727	2020.6
7	The relationship between zoonotic diseases and ecological and environmental problems caused by human activities and related risks	9	1256	2020.6
8	Detection of SARS-CoV-2 in wastewater and COVID-19 epidemiological surveillance based on wastewater	48	10547	2020.4
9	The status of insect declines, driving factors and solutions	32	8032	2020.3
10	Techno-economic assessment of CO_2 direct air capture	10	2749	2019.9

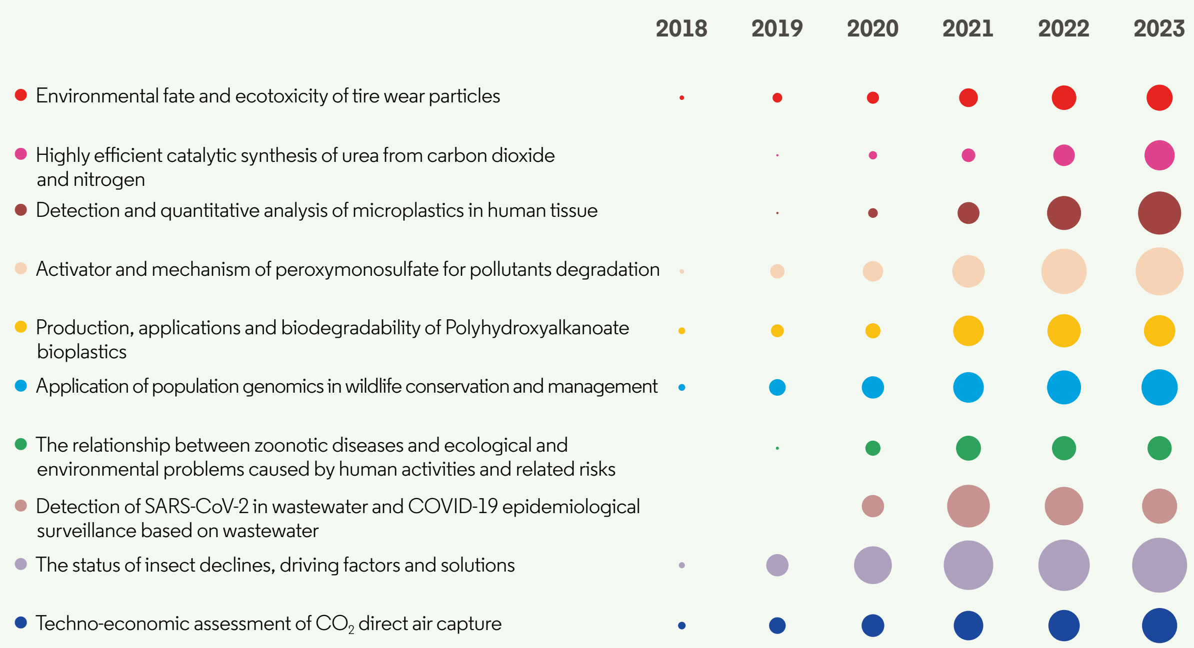


Figure 4: Citing papers for the Top 10 Research Fronts in ecology and environmental sciences

1.2 KEY HOT RESEARCH FRONT "Environmental fate and ecotoxicity of tire wear particles"

Tire wear particles (TWP) are particles generated from the friction between tires and roads, typically with a diameter smaller than 2.5μm. The tire manufacturing process requires the use of numerous chemicals. In addition to rubber, these chemicals might include fillers, reinforcing agents, processing aids, retarders, adhesives, and activators, resulting that TWP contain various environmental pollutants. TWP may also react with road surface materials or other traffic emissions under heat and friction to form new pollutants with complex compositions.

TWP and their transformation products can deposit on roads or roadsides, and then be washed into water bodies through rainfall runoff, subsequently entering aquatic biological systems. They release highly toxic pollutants with teratogenic and mutagenic properties, posing health risks to aquatic organisms. Approximately 3.1 billion tires are produced globally each year, with an average annual TWP emission of 0.81kg per person. Some studies have estimated that these particles account for half of the microplastics entering rivers, lakes, and oceans, along with 80% of microplastics in the air. The large-scale emissions of TWP into the environment and their associated pollution, along with the health hazards to organisms are receiving increasing attention.

This front includes 18 core papers. The earliest is a review article published in Water Research in 2018, co-authored by Reemtsma Thorsten from the Helmholtz Centre for Environmental Research in Germany, with collaborators including Hofmann Thilo from the University of Vienna, Austria. This paper has been cited 367 times at this writing, making it the most-cited core paper in this front. It reviews the properties, generation, quantitative analysis, emission, environmental behavior, and ecotoxicology of TWP. Estimates indicate that the European Union produces approximately 1,327,000 tons of TWP annually, while the USA produces about 1,120,000 tons of TWP per year. Between 0.1% and 10% of TWP eventually enter surface waters.

Among the pollutants caused by TWP, 6PPD-quinone is a key, highly toxic substance. More than half of the 18 core papers in this hot front focus on the environmental characteristics and ecotoxicology of 6PPD-quinone. The precursor of 6PPD-quinone is N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), a widely used tire rubber antioxidant. 6PPD readily transforms into 6PPD-quinone in ozone environments, and its environmental exposure poses significant risks to both organisms and human health. The second-most-cited paper in this front is a study published in *Science* in 2021, collaboratively authored by scientists from the USA and Canada. This paper proposes that 6PPD-quinone is the primary toxic substance responsible for the acute mortality of coho salmon associated with stormwater runoff in the Pacific Northwest of the USA.

6PPD-quinone is a derivative of the rubber antioxidant 6PPD, which is present in almost all tires. 6PPD-quinone is widely present globally and often reaches toxic concentrations. A core paper from Hong Kong, China, in this hot front revealed that six emerging p-Phenylenediamines (PPDs) and derivatives (6PPD-quinone) from TWP are ubiquitous in urban PM2.5 in China, with a total detection rate of 81%.

The need is urgent for further research into TWP-related pollution and ecotoxicological risks. At the same time, the global rubber tire industry faces pressing challenges for transformation to green manufacturing. The recently approved "Euro 7" emission standard has, for the first time, imposed restrictions on tire-emission pollution. The industry now confronts a critical need to manufacture products with lower 6PPD content or alternatives to 6PPD to reduce environmental pollution caused by TWP.

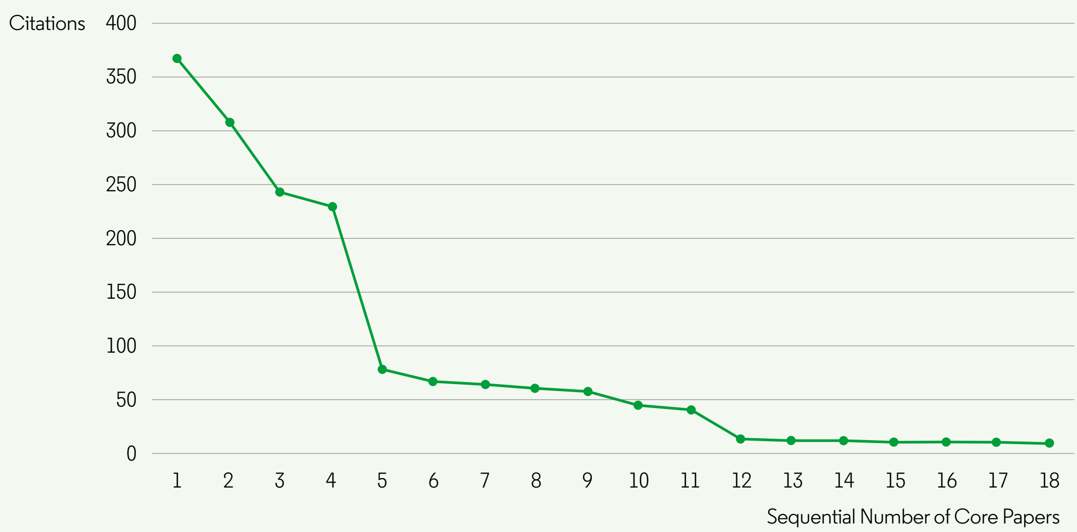


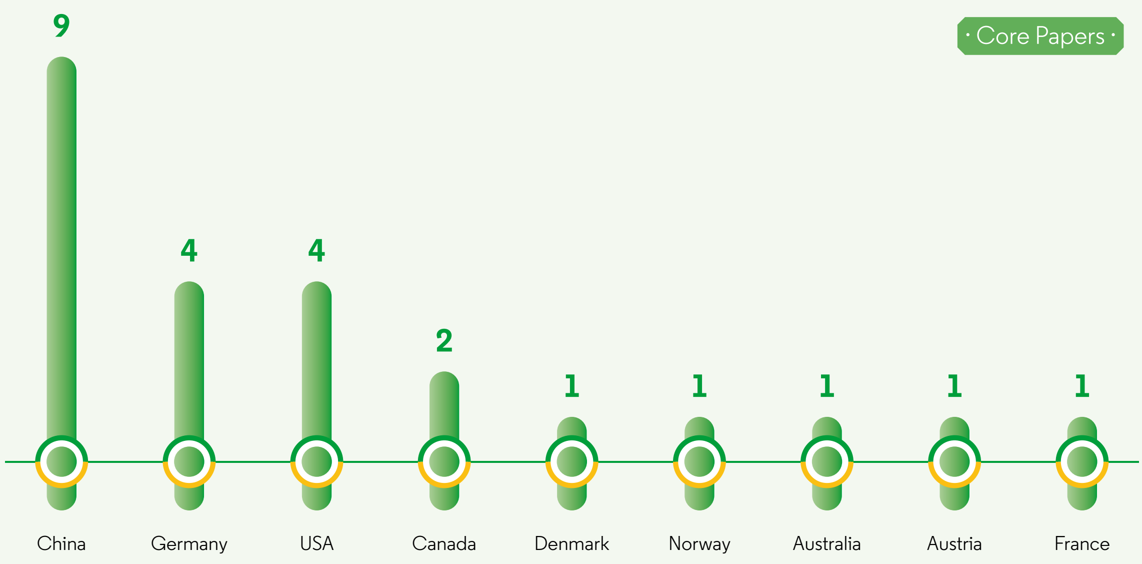
Figure 5: Citation frequency distribution curve of core papers in the Research Front "Environmental fate and ecotoxicity of tire wear particles"

Regarding the countries and institutions behind the core papers (Table 8): China is the largest contributor to this hot front, with nine core papers, accounting for half of the foundational reports. Both the USA and Germany have four core papers, tying for second place, each accounting for nearly a quarter of the core. Among the publishing institutions, Southeast University in China contributes four core papers, ranking 1st. Other institutions, including Hong Kong Baptist University and Zhejiang University of Technology from China, the University of Washington and Washington State University from the USA, the Helmholtz Association and German Federal Highway Research Institute in Germany, supply two core papers each.

Table 8: Top countries and institutions producing core papers in the Research Front "Environmental fate and ecotoxicity of tire wear particles"

Country Ranking	Country	Core Papers	Proportion
1	China	9	50.0%
2	Germany	4	22.2%
2	USA	4	22.2%
4	Canada	2	11.1%
5	Denmark	1	5.6%
5	Norway	1	5.6%
5	Australia	1	5.6%
5	Austria	1	5.6%
5	France	1	5.6%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Southeast University	China	4	22.2%
2	Hong Kong Baptist University	China	2	11.1%
2	University of Washington	USA	2	11.1%
2	Zhejiang University of Technology	China	2	11.1%
2	Washington State University	USA	2	11.1%
2	Helmholtz Association	Germany	2	11.1%
2	Federal Highway Research Institute	Germany	2	11.1%

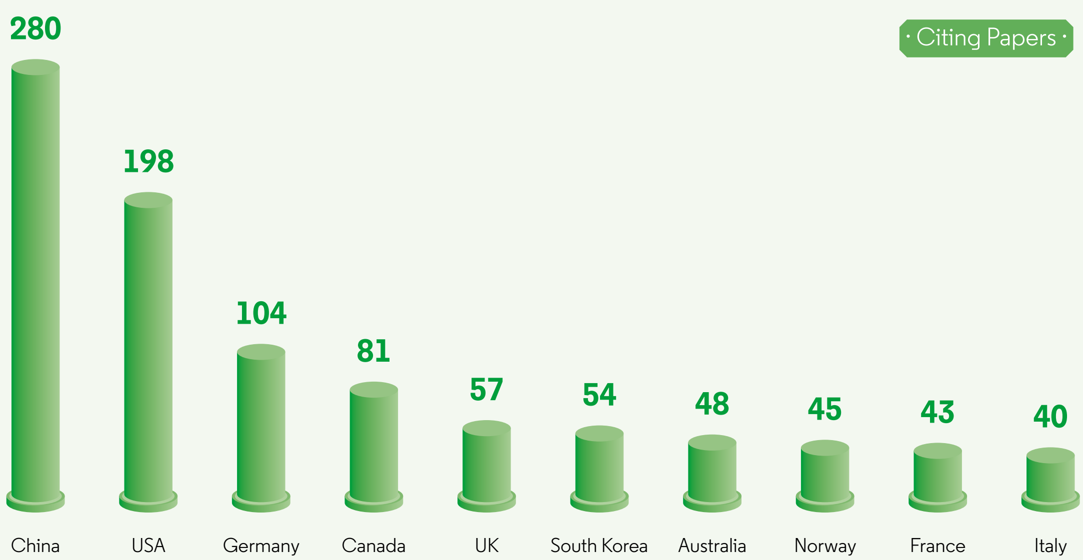


In terms of the countries and institutions citing the core papers (Table 9), China remains the country with the most citing papers in this front, with a total of 280, accounting for nearly one-third of the total. The USA and Germany rank 2nd and 3rd with 198 and 104 citing papers, respectively. Among the top institutions producing citing papers, four are based in China, with the Chinese Academy of Sciences contributing the highest number at 45 papers. The Helmholtz Association of Germany and the National Center for Scientific Research of France (CNRS) rank 2nd and 3rd with 36 and 24 citing papers, respectively.

Table 9: Top countries and institutions producing citing papers in the Research Front "Environmental fate and ecotoxicity of tire wear particles"

Country Ranking	Country	Citing Papers	Proportion
1	China	280	30.4%
2	USA	198	21.5%
3	Germany	104	11.3%
4	Canada	81	8.8%
5	UK	57	6.2%
6	South Korea	54	5.9%
7	Australia	48	5.2%
8	Norway	45	4.9%
9	France	43	4.7%
10	Italy	40	4.3%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	45	4.9%
2	Helmholtz Association	Germany	36	3.9%
3	National Center for Scientific Research of France (CNRS)	France	24	2.6%
4	University of Toronto	Canada	19	2.1%
5	Norwegian Institute for Water Research	Norway	18	2.0%
5	Southeast University - China	China	18	2.0%
5	University of Washington	USA	18	2.0%
5	Zhejiang University of Technology	China	18	2.0%
9	University of Queensland	Australia	16	1.7%
10	Hong Kong Baptist University	China	15	1.6%
10	Washington State University	USA	15	1.6%



1.3 KEY HOT RESEARCH FRONT "Techno-economic assessment of CO_2 direct air capture"

CO_2 direct air capture (DAC) is an emerging negative-carbon technology that typically uses low-carbon energy sources such as wind, solar, and geothermal energy to directly capture low-concentration carbon dioxide from the air, achieving net negative CO_2 emissions. DAC is suitable for CO_2 capture from distributed sources and mobile sources such as small fossil fuel combustion devices and vehicles. The placement of DAC installations is highly flexible and can capture CO_2 leaked during other Carbon Capture, Utilization, and Storage (CCUS) processes. It is a key technological means and backup technology for achieving climate-change temperature control goals, playing an important role in limiting global warming to within 2°C . DAC is increasingly receiving widespread attention. However, in practical applications, DAC faces scientific challenges, including high energy consumption for capture, high cost of adsorption materials, insufficient CO_2 adsorption capacity, and the need for the integration and optimization of process systems. These limitations have restricted its current large-scale promotion and application.

At present, the development of DAC technology is still in its early stages globally, with some demonstration projects constructed. The world's first industrial-scale DAC plant was built in Iceland in 2021, with an annual CO_2 capture capacity of 4,000 tons. The key to the future development and promotion of DAC lies in effectively reducing costs and improving efficiency.

Ten core papers anchor this hot front, mainly focusing on DAC technology process development and technical-economic assessments such as life cycle assessment, economic evaluation, and energy assessment of DAC. The most-cited paper, with 674 citations to date, was *published* in the journal *Joule* in 2018 by American and Canadian scholars, including David Keith, a professor of applied physics at Harvard University. This paper introduces a continuous DAC process using an aqueous KOH (potassium hydroxide) sorbent coupled to a calcium caustic recovery loop, and provides energy use estimation, material and energy simulation, and cost assessment for this process.

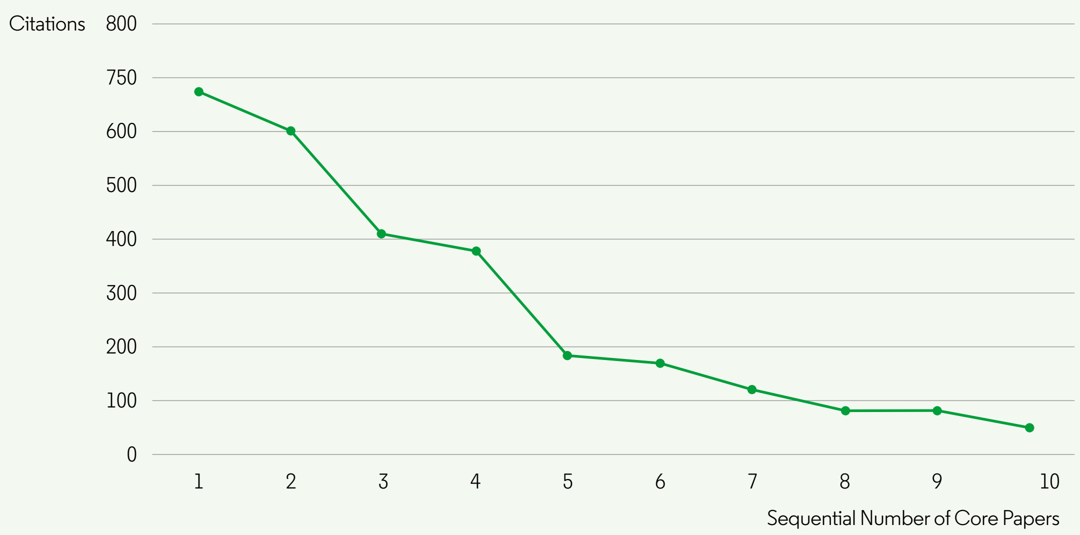


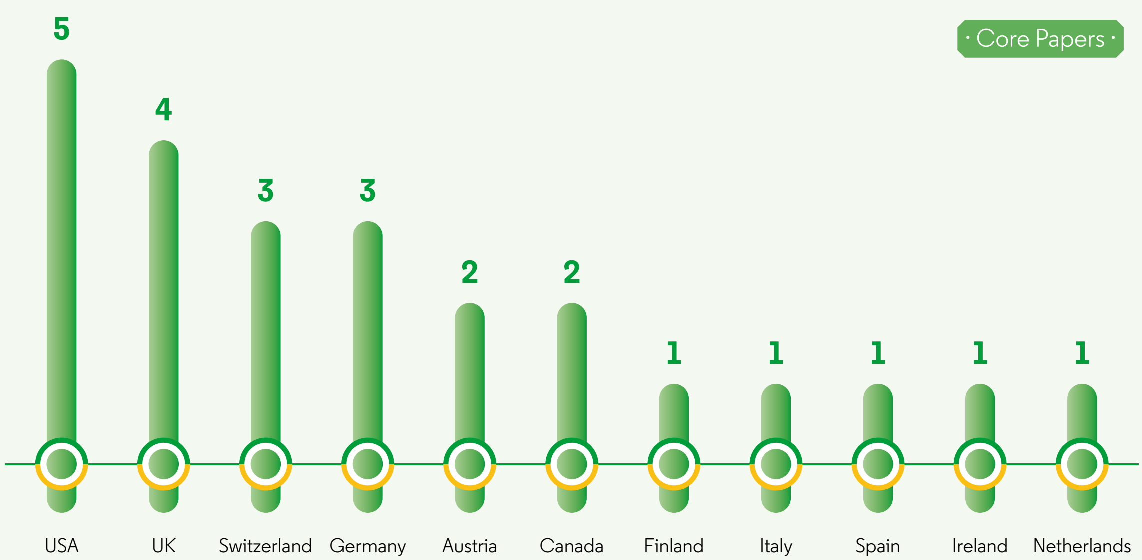
Figure 6: Citation frequency distribution curve of core papers in Research Front "Techno-economic assessment of CO_2 direct air capture"

Statistics on the countries and institutions in this front (Table 10) indicate that the USA is the largest producer of core papers, with a total of five, accounting for half of the total core papers. The UK follows closely, contributing four core papers. Switzerland and Germany both have three core papers, tying for 3rd place. Among the publishing institutions, the Swiss Federal Institute of Technology (ETH) Zurich has the highest number, with three core papers. Other institutions include four research institutions in Germany, three in the UK, and two based in the USA, each contributing two core papers.

Table 10: Top countries and institutions producing core papers in the Research Front "Techno-economic assessment of CO_2 direct air capture"

Country Ranking	Country	Core Papers	Proportion
1	USA	5	50.0%
2	UK	4	40.0%
3	Switzerland	3	30.0%
3	Germany	3	30.0%
5	Austria	2	20.0%
5	Canada	2	20.0%
7	Finland	1	10.0%
7	Italy	1	10.0%
7	Spain	1	10.0%
7	Ireland	1	10.0%
7	Netherlands	1	10.0%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Swiss Federal Institute of Technology Zurich	Switzerland	3	30.0%
2	Technical University of Berlin	Germany	2	20.0%
2	International Institute for Applied Systems Analysis	Austria	2	20.0%
2	Imperial College London	UK	2	20.0%
2	University of Wisconsin Madison	USA	2	20.0%
2	University of Hamburg	Germany	2	20.0%
2	University of Leeds	UK	2	20.0%
2	Mercator Research Institute on Global Commons and Climate Change	Germany	2	20.0%
2	Potsdam Institute for Climate Impact Research	Germany	2	20.0%
2	University of Aberdeen	UK	2	20.0%
2	Colorado School Mines	USA	2	20.0%



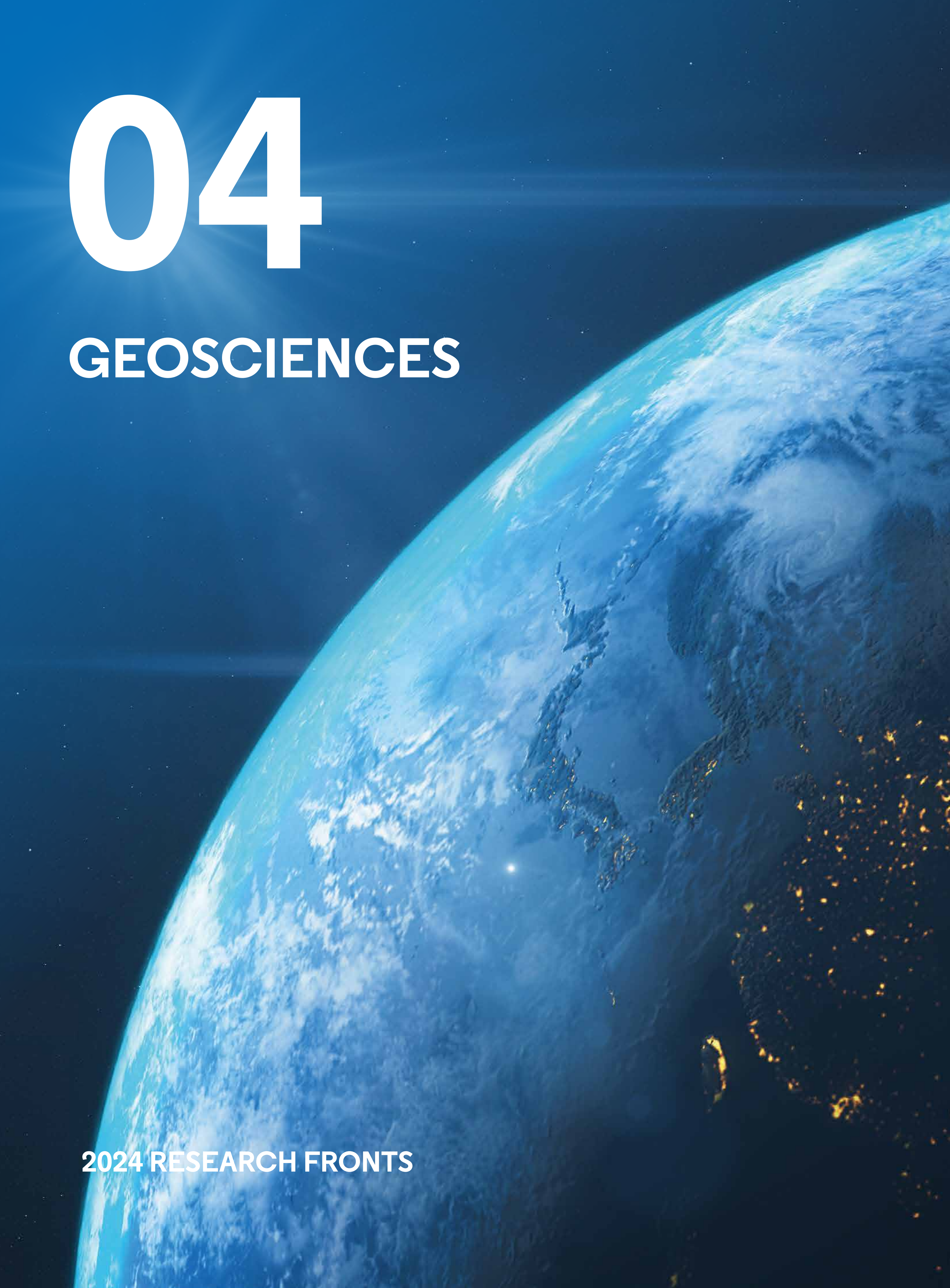
From the perspective of citing papers by country and institution (Table 11), the USA has the highest number of citing papers with 559, accounting for nearly one-third of the total. The UK and Germany rank 2nd and 3rd with 343 and 293 papers, respectively. China ranks 4th with a contribution of 281 citing papers. Among the citing institutions, the United States Department of Energy (DOE) contributes the most, with 109 citing papers, accounting for 5.9% of the total. ETH Zurich and Imperial College London contribute 90 and 73 citing papers respectively, ranking 2nd and 3rd.

Table 11: Top countries and institutions producing citing papers in the Research Front "Techno-economic assessment of CO_2 direct air capture"

Country Ranking	Country	Citing Papers	Proportion
1	USA	559	30.4%
2	UK	343	18.6%
3	Germany	293	15.9%
4	China	281	15.3%
5	Canada	143	7.8%
6	Switzerland	138	7.5%
7	Netherlands	136	7.4%
8	Australia	124	6.7%
9	France	89	4.8%
10	Italy	83	4.5%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	United States Department of Energy (DOE)	USA	109	5.9%
2	Swiss Federal Institute of Technology Zurich	Switzerland	90	4.9%
3	Imperial College London	UK	73	4.0%
4	Helmholtz Association	Germany	71	3.9%
5	Lappeenranta-Lahti University of Technology	Finland	60	3.3%
6	International Institute for Applied Systems Analysis	Austria	59	3.2%
7	Potsdam Institute for Climate Impact Research	Germany	45	2.4%
8	Chinese Academy of Sciences	China	43	2.3%
9	Utrecht University	Netherlands	42	2.3%
10	National Center for Scientific Research of France (CNRS)	France	40	2.2%


2024 RESEARCH FRONTS



04

GEOSCIENCES

2024 RESEARCH FRONTS

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN GEOSCIENCES

In 2024, the distribution of the Top 10 Research Fronts in geosciences is relatively balanced. In the field of geology, "Technical potential and development for hydrogen storage", and "Survival characteristics and enrichment extraction of rare earth elements in coal" both represent national strategic needs that are increasingly emphasized by various countries and can effectively drive the development of material equipment technology and high-tech industries.

Two Research Fronts demonstrate the active response of the geological community to the deep societal concern over human activity and its effect on climate change: In the field of atmospheric science, "Types and drivers of complex extreme weather and climate events" registers among the Top 10, with the field of geography represented by "The impact of climate change on forest resilience after wildfires in the western United States." In the field of planetary science, reliance on important exploration platforms such as Insight, Hayabusa 2, OSIRIS-REx, Mars and asteroid exploration continues to produce new high-value discoveries. "Insight's seismic experiment on Mars" and "Analysis of Asteroid Surface Characteristics and Sample Composition" have been featured multiple times in previous Research Fronts roundups. At the same time, basic research and technical applications such as "Holocene temperature conundrum", "Mapping global forest canopy height through integration of GEDI and Landsat data", and "Radiocarbon age calibration curves, data sets, and applications" highlight the enormous potential and vitality of geosciences research.

Table 12: Top10 Research Fronts in geosciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Technical potential and development for hydrogen storage	40	3001	2021.8
2	Global Impact of the Tonga Volcanic Eruption	33	2002	2021.7
3	Insight's seismic experiment on Mars	25	1781	2021.6
4	Analysis of Asteroid Surface Characteristics and Sample Composition	22	2507	2021.0
5	Survival characteristics and enrichment extraction of rare earth elements in coal	15	1492	2020.9
6	Radiocarbon age calibration curves, data sets, and applications	6	4200	2020.5
7	Mapping global forest canopy height through integration of GEDI and Landsat data	16	1945	2020.4
8	The impact of climate change on forest resilience after wildfires in the western United States	10	1481	2020.3
9	Types and drivers of complex extreme weather and climate events	10	2195	2020.2
10	Holocene temperature conundrum	8	1108	2020.1

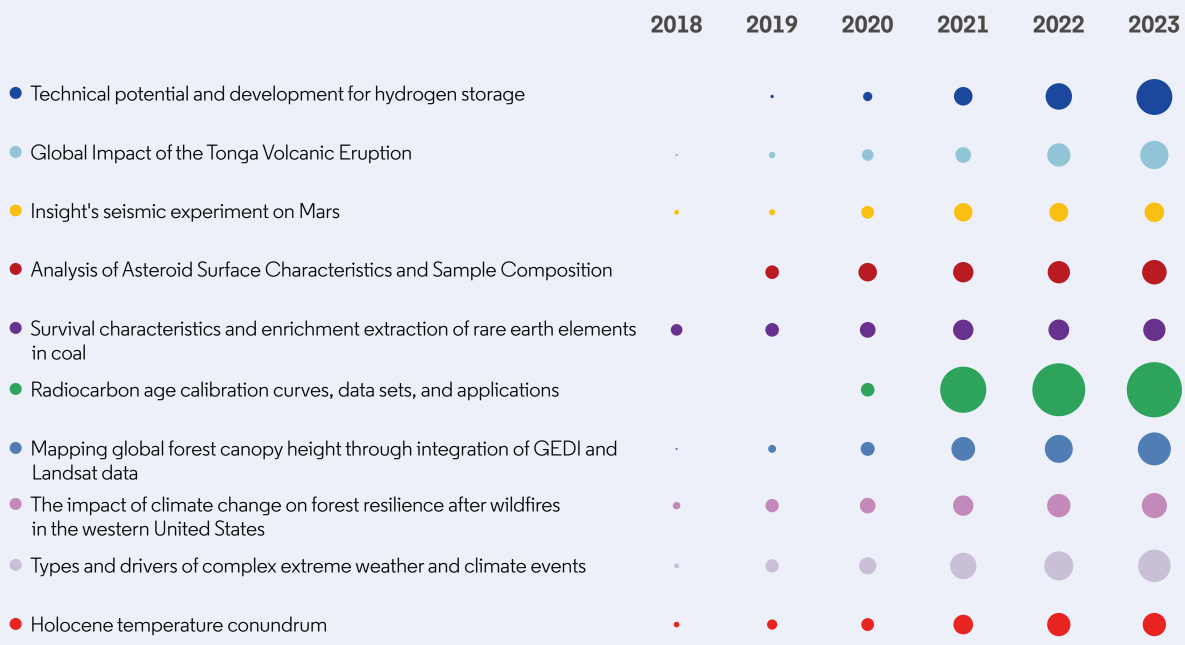


Figure 7: Citing papers for the Top 10 Research Fronts in geosciences

1.2 KEY HOT RESEARCH FRONT – "Technical potential and development for hydrogen storage"

Underground hydrogen storage utilizes subterranean geological structures to achieve large-scale high-pressure gaseous storage of hydrogen energy. This involves injecting hydrogen into underground sites such as salt caves, depleted oil and gas reservoirs, aquifers, abandoned mines, and other underground places for closed storage. This method has the advantages of high safety, low cost, large scale, long cycle, and cross-season energy storage, making it an important development direction for large-scale hydrogen energy reserves in the future.

Europe is one of the regions with the richest geological hydrogen storage projects in the world. Germany, the Netherlands, the UK, and Poland, are among the main hydrogen producers in Europe. Since the 1970s, full-scale experiments and industrial demonstrations of hydrogen storage in salt caverns, depleted gas reservoirs, and aquifers have been conducted successively. These activities have accumulated rich research experience in evaluating and selecting geological sites, designing reservoir capacity, standardizing the process of reservoir construction, and monitoring hydrogen-storage reservoir operation. Countries such as Australia, Saudi Arabia, Brazil, which possess immense potential for renewable resources, have also been actively seeking strategic positioning in the rapidly rising hydrogen energy market in recent years, promoting the implementation of a series of hydrogen energy pilot projects.

Fourteen of the 40 core papers in this hot front are review articles. "Underground hydrogen storage: Characteristics and prospects" published in *Renewable and Sustainable Energy Reviews* by R. Tarkowsi, Mineral and Energy Economy Research Institute, Polish Academy of Sciences, has attracted the most citations to date. This research emphasizes that geological, technological, economic, legal, and social obstacles must be addressed before implementing underground hydrogen-storage projects: the report also proposes roles that the governments, non-governmental bodies, universities, research institutes, and industry can each play in the project roadmap. The remaining 26 research articles focus on the characteristics of different types of hydrogen storage, as well as the impact of different geological and climatic conditions on hydrogen storage facilities. "Technical potential of salt caverns for hydrogen storage in Europe" published in *International Journal of Hydrogen Energy* by authors at RWTH Aachen University and Forschungszentrum Jülich, provides a suitability assessment of European subsurface salt structures in terms of size, land eligibility and storage capacity. The study found that, considering only onshore and offshore salt caverns, Germany has the highest hydrogen storage potential at 9.4 gigawatt-hours, followed by Poland at 7.24 gigawatt-hours.

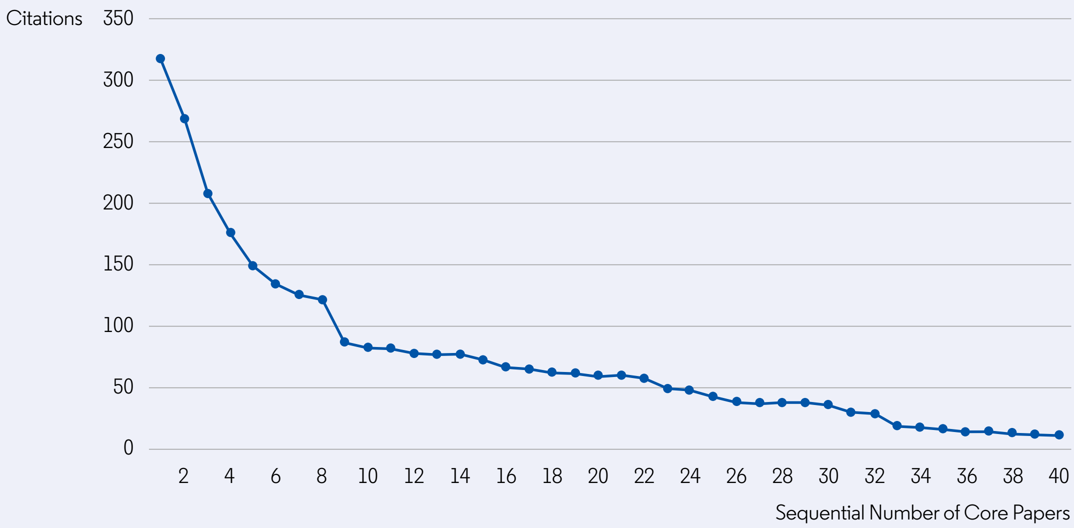


Figure 8: Citation frequency distribution curve of core papers in the Research Front "Technical potential and development for hydrogen storage"

In this Research Front, Australia has shown the most active performance, with Australia-based researchers accounting for 55% of the total core papers published. Among the Australian institutions, the Edith Cowan University has actively engaged in international collaboration with resource-based Gulf countries to enhance its academic influence. Among its 16 core papers produced, 12 were in collaboration with institutions in Saudi Arabia, five with Iran, and three with institutions in Iraqi. This university has established a center for sustainable energy and resources, focusing on research areas such as carbon capture and storage, and blue and green hydrogen production.

Table 13: Top countries and institutions producing core papers in the Research Front "Technical potential and development for hydrogen storage"

Country Ranking	Country	Core Papers	Proportion
1	Australia	22	55.0%
2	Saudi Arabia	12	30.0%
3	UK	7	17.5%
4	Netherlands	6	15.0%
5	Malaysia	5	12.5%
5	Iran	5	12.5%
7	USA	4	10.0%
7	China	4	10.0%
9	Iraq	3	7.5%
9	Norway	3	7.5%

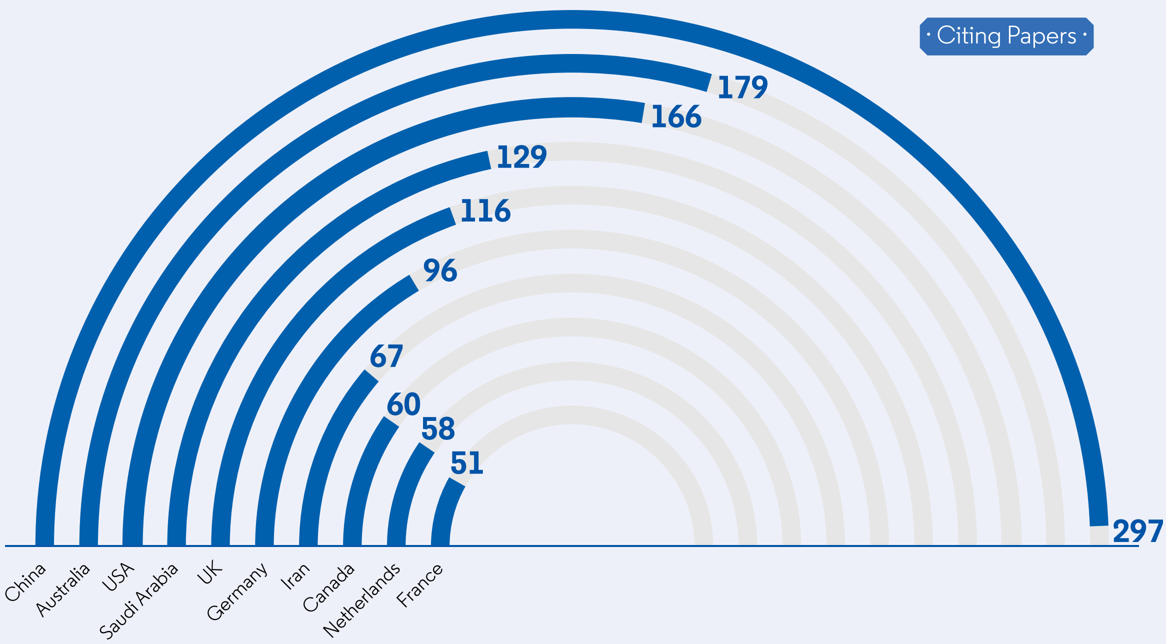
Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Edith Cowan University	Australia	16	40.0%
2	King Abdullah University of Science & Technology	Saudi Arabia	8	20.0%
3	Curtin University	Australia	6	15.0%
3	King Fahd University of Petroleum and Minerals	Saudi Arabia	6	15.0%
5	University of Edinburgh	UK	5	12.5%
6	Imperial College London	UK	4	10.0%
6	Delft University of Technology	Netherlands	4	10.0%
8	Commonwealth Scientific & Industrial Research Organisation (CSIRO)	Australia	3	7.5%
8	University College Seaya International	Malaysia	3	7.5%
8	Universiti Teknologi Petronas	Malaysia	3	7.5%
8	Amirkabir University of Technology	Iran	3	7.5%

As for countries producing the most citing papers, China has actively followed up on research in this Research Front, followed by Australia, the USA, and Saudi Arabia. In terms of institutions producing the citing papers, Edith Cowan University performed most prominently. China University of Petroleum ranks 4th in the list of citing institutions.

Table 14: Top countries and institutions producing citing papers in the Research Front "Technical potential and development for hydrogen storage"

Country Ranking	Country	Citing Papers	Proportion
1	China	297	27.1%
2	Australia	179	16.4%
3	USA	166	15.2%
4	Saudi Arabia	129	11.8%
5	UK	116	10.6%
6	Germany	96	8.8%
7	Iran	67	6.1%
8	Canada	60	5.5%
9	Netherlands	58	5.3%
10	France	51	4.7%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Edith Cowan University	Australia	101	9.2%
2	King Fahd University of Petroleum and Minerals	Saudi Arabia	79	7.2%
3	Curtin University	Australia	53	4.8%
4	China University of Petroleum	China	52	4.8%
5	King Abdullah University of Science & Technology	Saudi Arabia	50	4.6%
6	Chinese Academy of Sciences	China	39	3.6%
7	United States Department of Energy (DOE)	USA	29	2.7%
8	Helmholtz Association	Germany	28	2.6%
9	Delft University of Technology	Netherlands	27	2.5%
9	Khalifa University	UNITED ARAB EMIRATES	27	2.5%



1.3 KEY HOT RESARCH FRONT – "Holocene temperature conundrum"

The Holocene is the youngest geologic epoch and the most recent interglacial interval. Resolving the evolution of global surface temperatures during this critical period provides an excellent opportunity to better understand the mechanisms, as well as the timescale, of large-scale climate change of the Earth system. This research may also help in evaluating the current climate and environment issues associated with global warming in the longer-term context of natural climate variability, especially the impact and role of human activities, while also providing valuable scientific evidence for formulating strategies to respond to ongoing and future climate change.

Both climate model simulations and proxy reconstructions are widely used in the study of Holocene temperature. Significant divergence between simulations and reconstructions is revealed in many research papers, primarily for northern mid-high latitudes. One of the most prominent differences between the results of the two methods is the long-warming temperature trend during the Holocene, along with an apparently mismatched cooling trend. These findings have resulted in a phenomenon termed the Holocene temperature conundrum, which has challenged paleoclimatologists for the past decade.

This front consists of eight core papers, focusing on enhancing the understanding and analysis of Holocene temperature changes through improved climate models and the development of proxy indicators. Among these papers, the most prominent research theme concerns how to integrate paleoclimate proxy records and simulation comparisons. The papers reveal that paleoclimate data assimilation plays an important role in reconciling the divergence between proxy records and simulations. "Globally resolved surface temperatures since the last glacial maximum" is the most citied paper, in which Jessica E. Tierney, a key member of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment report, is one of the authors. This paper constructs a trend of global surface temperature changes since the last glacial maximum and reveals two primary driving mechanisms: the radiative forcing of ice sheets and greenhouse gases, along with the superposition of changes in the ocean overturning circulation and seasonal insolation.

The results also indicate that both the rate and magnitude of warming in the 20th and 21st century are unusual, leading to widespread concern. In the development of climate model simulation and proxy reconstructions, the relevant core papers emphasize an approach using multi-method ensembles of quantitative reconstruction and integrations of multi-proxy data. Researchers have also developed a method of transforming seasonal temperature into annual temperature, enhancing the study of the Holocene temperature conundrum. In terms of model evaluation, related research evaluated and compared the simulation results of Paleoclimate Model Intercomparison Project (PMIP4) under the new round of the Coupled Model Intercomparison Project (CMIP6) – hereafter referred to as PMIP4-CMIP6. The results indicate that the latest models' simulated climate change trends are generally consistent with theoretical predictions and observational data.

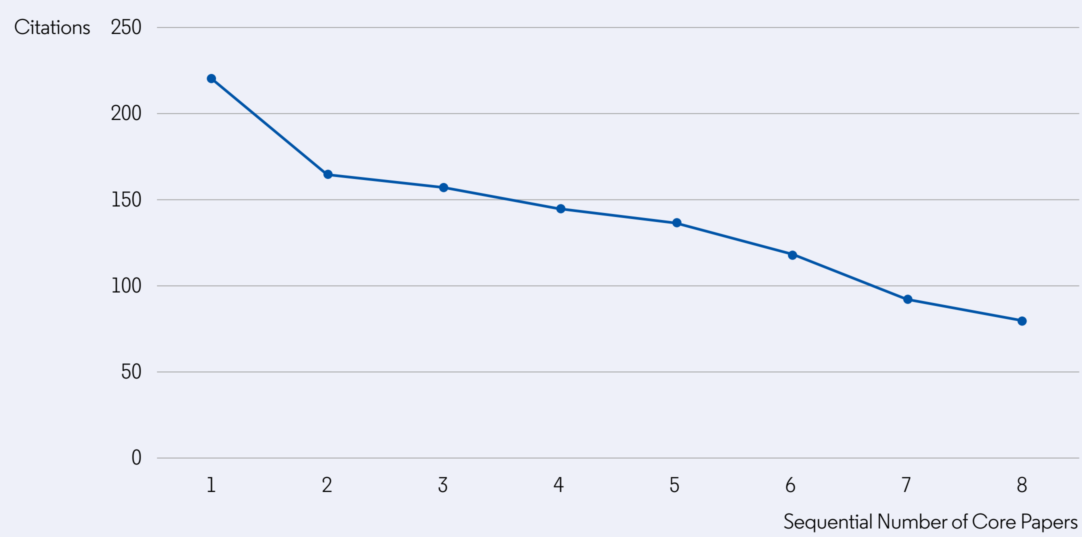


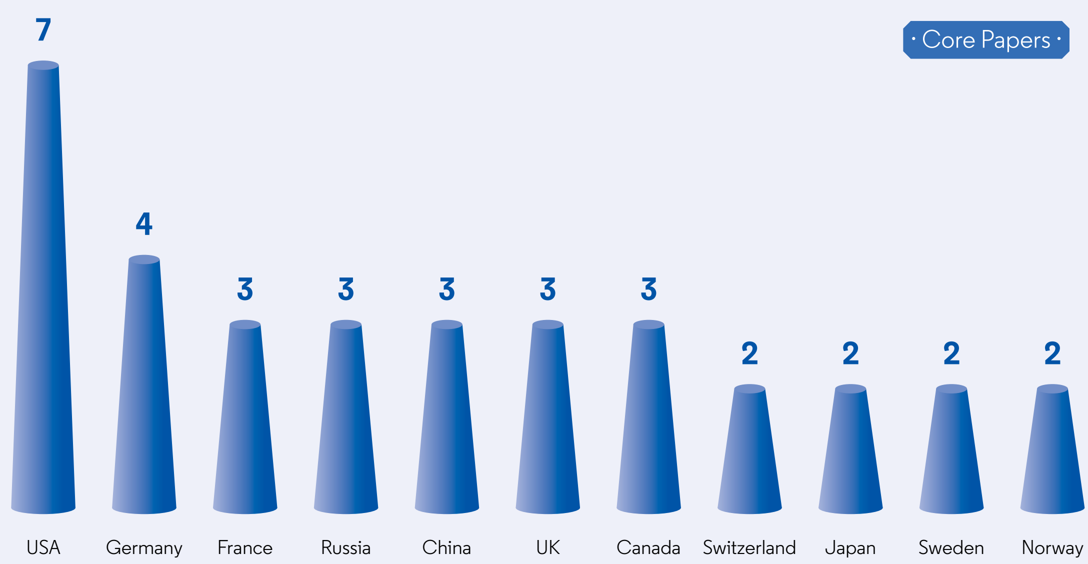
Figure 9: Citation frequency distribution curve of core papers in Research Front "Holocene temperature conundrum"

Multiple countries are involved in the research and development work of this front, with the USA holding a leading advantage in contributions to the core papers (Table 15). Top research institutions in the USA and Europe dominate the rankings of the most productive institutions, including the University of Arizona, the National Center for Atmospheric Research, the Helmholtz Association, the Russian Academy of Sciences, the National Center for Scientific Research of France, among other institutions. Some Chinese institutions, such as the Chinese Academy of Sciences, Northwest University, Nanjing Normal University, Qingdao National Laboratory for Marine Science and Technology, Nanjing University of Information Science and Technology, National Taiwan University, also contribute to the core papers.

Table 15: Top countries and institutions producing core papers in the Research Front "Holocene temperature conundrum"

Country Ranking	Country	Core Papers	Proportion
1	USA	7	87.5%
2	Germany	4	50.0%
3	France	3	37.5%
3	Russia	3	37.5%
3	China	3	37.5%
3	UK	3	37.5%
3	Canada	3	37.5%
8	Switzerland	2	25.0%
8	Japan	2	25.0%
8	Sweden	2	25.0%
8	Norway	2	25.0%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of Arizona	USA	4	50.0%
1	National Center for Atmospheric Research (NCAR)	USA	4	50.0%
1	Helmholtz Association	Germany	4	50.0%
4	University of Paris Cite	France	3	37.5%
4	National Center for Scientific Research of France (CNRS)	France	3	37.5%
4	University of Paris Saclay	France	3	37.5%
4	French Alternative Energies and Atomic Energy Commission (CEA)	France	3	37.5%
4	Northern Arizona University	USA	3	37.5%
4	University of Michigan	USA	3	37.5%
4	Max Planck Society	Germany	3	37.5%
4	Alfred Wegener Institute for Polar and Marine Research	Germany	3	37.5%
4	Russian Academy of Sciences	Russia	3	37.5%

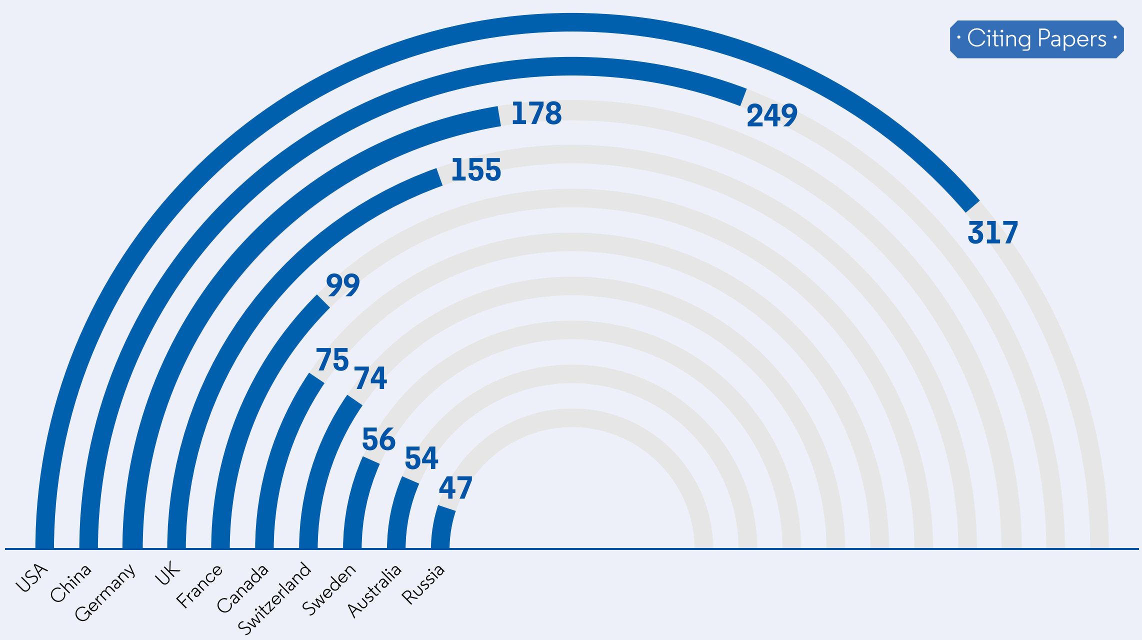


As for countries and institutions producing the most citing papers (Table 16), the USA ranks 1st. China is highly attentive to research advancements in this area, with the Chinese Academy of Sciences contributing the most numerous citing papers, and Lanzhou University also making the list. Institutions such as the Helmholtz Association, the Alfred Wegener Institute for Polar and Marine Research, the National Center for Scientific Research of France, and the University of Arizona can also boast a substantial output of follow-up research.

Table 16: Top countries and institutions producing citing papers in the Research Front "Holocene temperature conundrum"

Country Ranking	Country	Citing Paper	Proportion
1	USA	317	40.7%
2	China	249	32.0%
3	Germany	178	22.8%
4	UK	155	19.9%
5	France	99	12.7%
6	Canada	75	9.6%
7	Switzerland	74	9.5%
8	Sweden	56	7.2%
9	Australia	54	6.9%
10	Russia	47	6.0%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	140	18.0%
2	Helmholtz Association	Germany	101	13.0%
3	National Center for Scientific Research of France (CNRS)	France	91	11.7%
4	Alfred Wegener Institute for Polar and Marine Research	Germany	75	9.6%
5	University of Bremen	Germany	49	6.3%
6	University of Paris Cite	France	48	6.2%
7	University of Arizona	USA	46	5.9%
7	University of Paris Saclay	France	46	5.9%
9	French Alternative Energies and Atomic Energy Commission (CEA)	France	42	5.4%
10	Lanzhou University	China	39	5.0%



05

CLINICAL MEDICINE

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN CLINICAL MEDICINE

The Top10 Research Fronts in clinical medicine focus mainly on the application of immunotherapy or molecular targeted drugs in cancer, Alzheimer's disease, asthma, and diabetes. This trend basically continues the high level of research interest in immunotherapy and molecular targeted treatment of tumor and other difficult diseases in recent years. The current status of artificial intelligence (AI) and its prospects for application in clinical medicine (for example, in dentistry) is also reflected in the Top 10 and, given the vigorous development of AI technology, is expected to widen its impact on clinical medicine and continue as a hot topic.

In addition, left atrial appendage occlusion, performed through minimally invasive interventional surgery, is a major innovative technique for preventing strokes caused by atrial fibrillation. Multiple clinical studies have confirmed that this technique can, to some extent, solve the problem of increased bleeding risk associated with lifelong anticoagulation therapy.

Also notable is the hot front "Characteristics of human monkeypox virus infection," which has evolved from the 2023 emerging front "Ongoing monkeypox infection outbreak".

Table 17: Top10 Research Fronts in clinical medicine

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Monoclonal antibody drugs for early Alzheimer's disease	13	2197	2022.2
2	Triple therapy of cystic fibrosis	42	4869	2021.6
3	Antibody-drug conjugates (ADCs) for breast cancer	27	3466	2021.4
4	Characteristics of human monkeypox virus infection	23	5587	2021.2
5	Monoclonal antibody drugs for severe asthma	40	5581	2021.2
6	Artificial intelligence and dentistry	36	2958	2021.2
7	Left atrial appendage occlusion technology for atrial fibrillation	24	2215	2021.2
8	Long-acting GLP-1 receptor agonists for type 2 diabetes	21	4776	2021.1
9	Immune checkpoint inhibitors for high metastatic colorectal cancer with DNA mismatch repair deficiency/microsatellite instability	11	4403	2021.0
10	Targeted therapy or immunotherapy for unresectable hepatocellular carcinoma	40	17831	2020.9

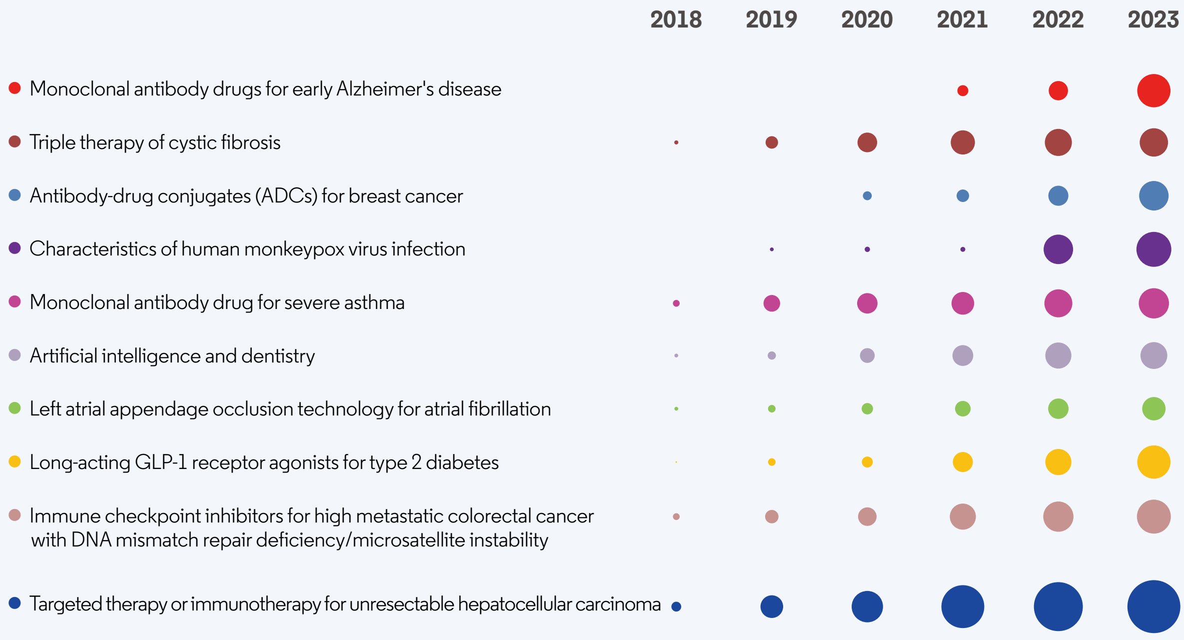


Figure 10: Citing papers for the Top10 Research Fronts in clinical medicine

1.2 KEY HOT RESEARCH FRONT – "Monoclonal antibody drugs for early Alzheimer's disease"

Alzheimer's disease (AD), with insidious onset, is a progressive and irreversible fatal neurodegenerative disease and the most important type of senile dementia. Its clinical manifestations mainly include memory decline, cognitive impairment, behavioral abnormalities, and life-function decline. Amyloid β (Aβ) deposition plays a key role in the pathogenesis of AD.

Removal of Aβ oligomers (soluble aggregates) and Aβ plaques (insoluble extracellular aggregates) can slow the progression of AD. Therefore, monoclonal antibody drugs that can reduce Aβ deposition have become a hot research direction in the development of new AD drugs, with many international pharmaceutical companies involved in this area.

The key hot research front "Monoclonal antibody drugs for early Alzheimer's Disease" includes 13 core papers, reporting clinical trials for various monoclonal antibody compounds for AD, including lecanemab, donanemab, aducanumab, crenezumab, and solanezumab. These trials assess the efficacy and safety of these drugs, reporting mixed results, with some trials showing positive outcomes and others less favorable findings.

Although adunizumab received conditional approval from the US Food and Drug Administration (FDA) in June 2021, conflicting results from two Phase III clinical trials published in *the Journal of Prevention of Alzheimer's Disease* in 2022 have led to controversy on the drug's clinical efficacy and safety. At present, the most successful new drug for AD is lecanemab, which plays a therapeutic role via targeting to bind soluble aggregate Aβ and then clear it in the brain.

The most-cited core paper specifies an 18-month Phase III clinical trial published in *the New England Journal of Medicine (NEJM)* in 2022, with results suggesting that lecanemab achieved the primary clinical endpoint and all key secondary clinical endpoints in clinical trials, demonstrating good efficacy. The drug was well tolerated, while infusion-related reactions were its most common adverse effects. Therefore, lecanemab was the first compound fully approved by the US FDA in January 2023 and was listed by *Science* as one of the top ten breakthroughs of 2023.

In addition, after multiple rounds of clinical trials, donanemab was also approved for sale in the USA in July 2024. However, these drugs have a short time to market, and longer-duration and larger-scale clinical trials are still needed to further determine their efficacy and safety for early AD, with special attention to their adverse reactions such as amyloid related imaging abnormalities (ARIA) including edema and bleeding. On the other hand, the development of crenezumab and solanezumab has failed because their clinical trial results did not confirm their effectiveness. Given the still-unclear pathogenesis of AD, drug development has never been smooth, and there is still a long way to go.

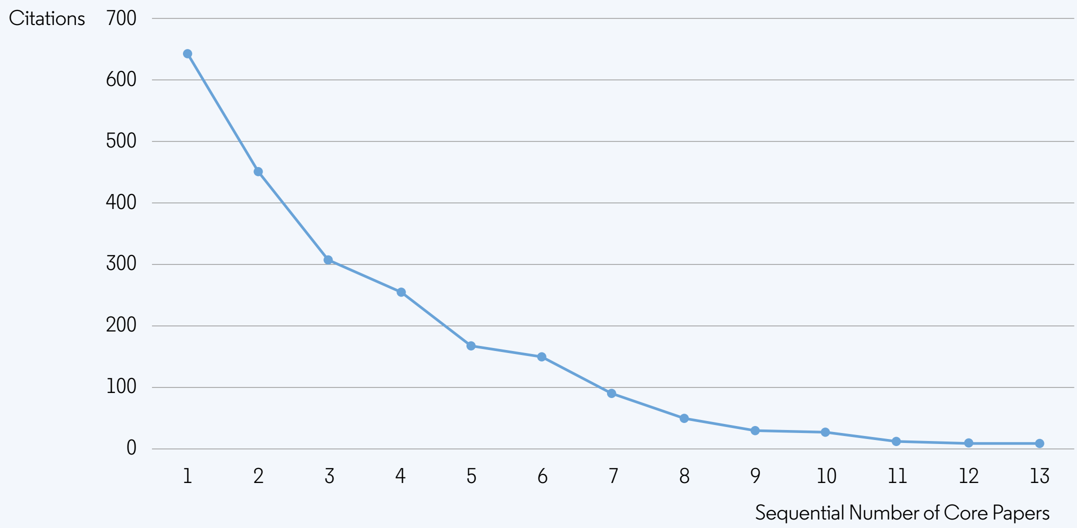


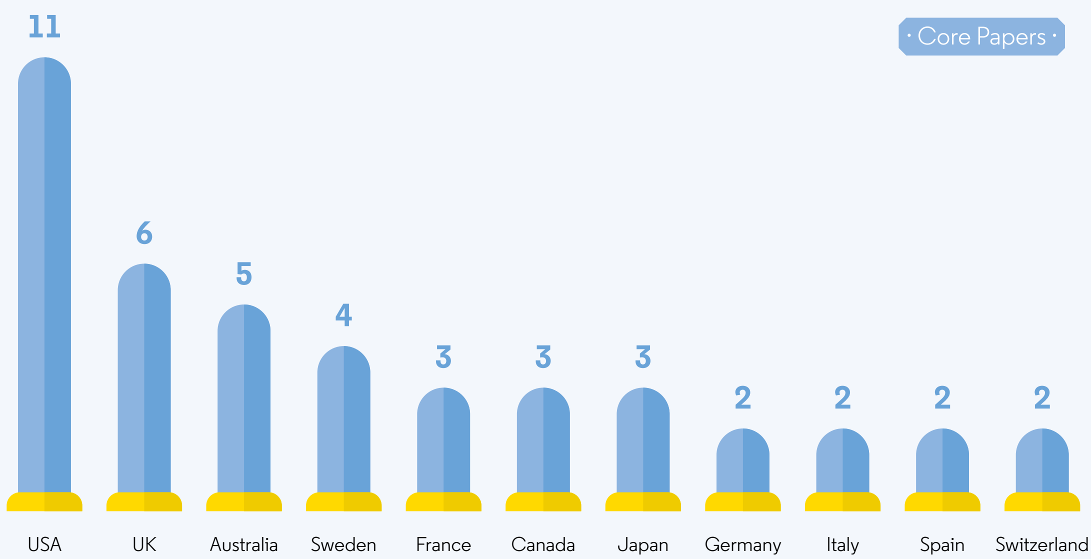
Figure 11: Citation frequency distribution curve of core papers in the Research Front "Monoclonal antibody drugs for early Alzheimer's disease"

Among the top countries producing core papers in this key hot front, the USA contributed more than 80% of the foundational documents, demonstrating significant advantage in the development of new AD drugs. More than half the top institutions producing core papers are based in the USA, with Yale University, the University of Southern California, and Brown University in the top three. A report on a lecanemab Phase III clinical study results, published by researchers at Yale University, is this front's most-cited core paper, and directly contributed to lecanemab receiving full approval for marketing by the US FDA.

Table 18: Top countries and institutions producing core papers in the Research Front "Monoclonal antibody drugs for early Alzheimer's disease"

Country Ranking	Country	Core Papers	Proportion
1	USA	11	84.6%
2	UK	6	46.2%
3	Australia	5	38.5%
4	Sweden	4	30.8%
5	France	3	23.1%
5	Canada	3	23.1%
5	Japan	3	23.1%
8	Germany	2	15.4%
8	Italy	2	15.4%
8	Spain	2	15.4%
8	Switzerland	2	15.4%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Yale University	USA	5	38.5%
2	University of Southern California	USA	4	30.8%
2	Brown University	USA	4	30.8%
2	University of Melbourne	Australia	4	30.8%
2	Eli Lilly	USA	4	30.8%
6	University of Tokyo	Japan	3	23.1%
6	Butler Hospital in Rhode Island	USA	3	23.1%
6	Harvard University	USA	3	23.1%
6	University of Toulouse	France	3	23.1%

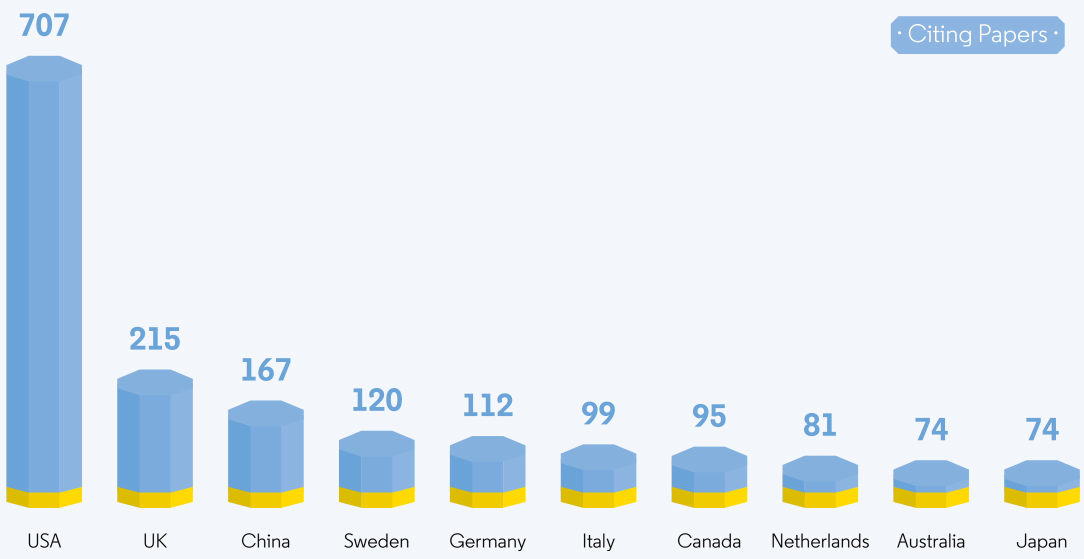


In terms of the citing papers, the USA contributed more than half, far surpassing other countries, reflecting the nation's active research presence and positive trajectory in the field of new AD drug development. China has also contributed 167 citing papers, indicating its ongoing attention and commitment to pursuing and advancing this research direction. The top 10 institutions producing citing papers are dominated by six USA institutions and four European institutions.

Table 19: Top countries and institutions producing citing papers in the Research Front "Monoclonal antibody drugs for early Alzheimer's disease"

Country Ranking	Country	Citing Papers	Proportion
1	USA	707	52.7%
2	UK	215	16.0%
3	China	167	12.4%
4	Sweden	120	8.9%
5	Germany	112	8.3%
6	Italy	99	7.4%
7	Canada	95	7.1%
8	Netherlands	81	6.0%
9	Australia	74	5.5%
10	Japan	74	5.5%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Harvard University	USA	114	8.5%
2	University College London	UK	93	6.9%
3	University of California San Francisco	USA	72	5.4%
4	Washington University in St. Louis	USA	66	4.9%
5	Massachusetts General Hospital	USA	62	4.6%
6	University of Southern California	USA	59	4.4%
7	Mayo Clinic	USA	57	4.2%
8	University of Gothenburg	Sweden	47	3.5%
9	Vrije University Amsterdam	Netherlands	46	3.4%
10	Helmholtz Association	Germany	45	3.4%



1.3 KEY HOT RESEARCH FRONT – "Targeted therapy or immunotherapy for unresectable hepatocellular carcinoma"

As the most common pathological type of primary liver cancer, hepatocellular carcinoma is characterized by hidden onset, rapid progression, and poor prognosis, representing a serious threat to human health. Most patients are diagnosed at an advanced stage and cannot undergo radical surgery. For these patients with unresectable hepatocellular carcinoma (uHCC), in addition to local treatment methods such as transcatheter arterial chemoembolization (TACE) and radiofrequency ablation, systematic drug therapy is also an important method to prolong survival time and improve quality of life.

With successive application of new drugs, such as multiple types of targeted drugs and immune checkpoint inhibitors in clinical practice, systemic drug therapy for uHCC has also evolved from the initial use of targeted single-drug and immune-therapy single-drug to the current stage of targeted-immune combination therapy. This progression has led to significant extension in patient survival, further solidifying the role of systemic drug therapy in the treatment of liver cancer.

The key hot research front "Targeted or immunotherapy for unresectable hepatocellular carcinoma" focuses on clinical efficacy and safety of targeted drugs such as sorafenib, lenvatinib, bevacizumab, and immune checkpoint inhibitors, such as atezolizumab, pembrolizumab, and camrelizumab for unresectable or advanced hepatocellular carcinoma.

Sorafenib, a multitarget antitumor drug, is the first targeted compound used in first-line treatment of uHCC, but its single-drug efficacy is not significant and only extends the median survival of patients by approximately three months. The results of the RFLECT study, published in *The Lancet* in 2018, suggested that another targeted drug, Lenvatinib, was more effective than sorafenib for unresectable liver cancer, and then became the second first-line targeted drug for uHCC, breaking the situation that sorafenib had dominated for many years. At the same time, rapid development of immune checkpoint inhibitors also brought systematic treatment of advanced hepatocellular carcinoma into the immunotherapy stage. Immune checkpoint inhibitors such as pembrolizumab showed good effects in clinical studies. Results from a Phase III clinical trial published in *The Lancet Oncology* in 2018 suggested that pembrolizumab is effective and tolerated in patients with advanced hepatocellular carcinoma who have previously been treated with sorafenib, and may serve as a new second-line treatment option for unresectable hepatocellular carcinoma. The most frequently cited core paper, with more than 3000 citations, is the IMbrave150 study, published in *NEJM* in 2020. The study reported that, in patients with uHCC, the combination of atezolizumab and bevacizumab significantly improved overall survival (OS), and progression-free survival (PFS) compared to sorafenib. This combination therapy has since been included in the first-line recommendation of advanced hepatocellular carcinoma by international clinical guidelines. This study was the first globally to adopt a new model of targeted combined immunotherapy for unresectable hepatocellular carcinoma, establishing a new treatment paradigm for systemic drug therapy in uHCC.

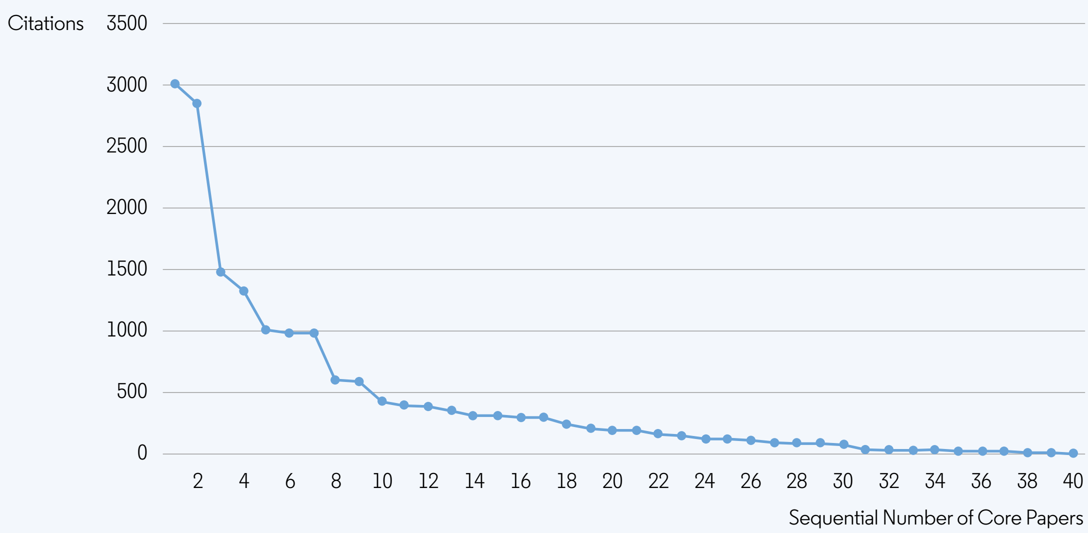


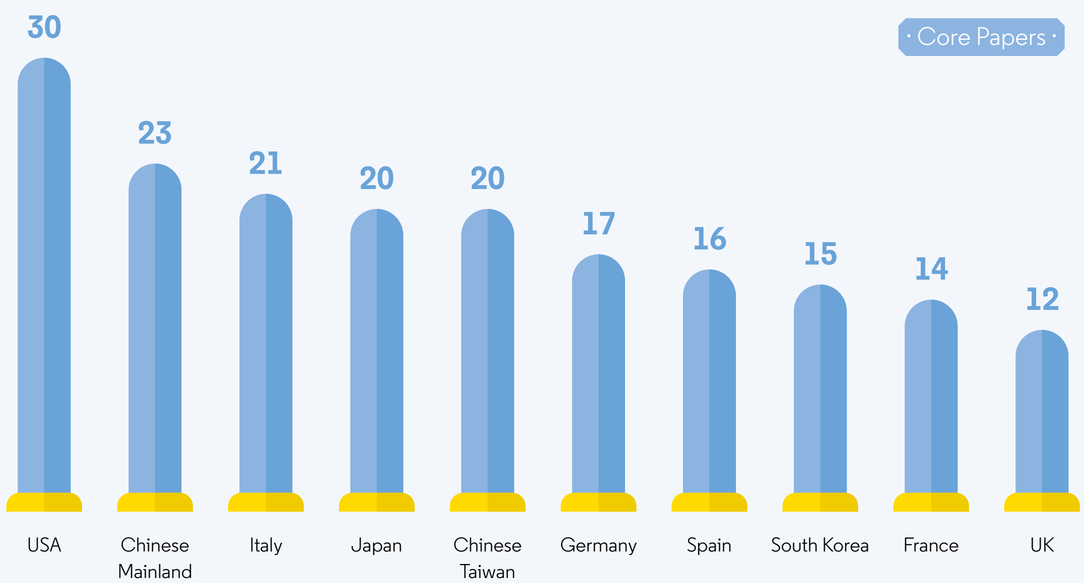
Figure 12: Citation frequency distribution curve of core papers in the Research Front "Targeted therapy or immunotherapy for unresectable hepatocellular carcinoma"

Forty core papers underlie this key research front. Among the top countries/regions, the USA has the highest contribution rate, followed by China. Other Asian countries or regions, such as Japan, Chinese Taiwan, and South Korea, are also on the list. This indicates that Asian countries or regions, as areas with a high incidence of liver cancer, generally place more emphasis on liver cancer treatment research, with higher research activity. Nearly half of the top institutions producing core papers are based in Asia, reflecting the same trend.

Table 20: Top countries/regions and institutions producing core papers in the Research Front "Targeted therapy or immunotherapy for unresectable hepatocellular carcinoma"

Country/region Ranking	Country/region	Core Papers	Proportion
1	USA	30	75.0%
2	Chinese Mainland	23	57.5%
3	Italy	21	52.5%
4	Japan	20	50.0%
4	Chinese Taiwan	20	50.0%
6	Germany	17	42.5%
7	Spain	16	40.0%
8	South Korea	15	37.5%
9	France	14	35.0%
10	UK	12	30.0%

Institution Ranking	Institution	Affiliated Country/region	Core Papers	Proportion
1	Kindai University	Japan	17	42.5%
2	National Taiwan University	Chinese Taiwan	14	35.0%
3	University of California Los Angeles	USA	13	32.5%
4	Massachusetts General Hospital	USA	11	27.5%
4	CIBEREHD	Spain	11	27.5%
4	University of Barcelona	Spain	11	27.5%
4	Harvard University	USA	11	27.5%
4	Humanitas University	Italy	11	27.5%
9	University of Ulsan	South Korea	10	25.0%
9	Hospital Clinic Barcelona	Spain	10	25.0%

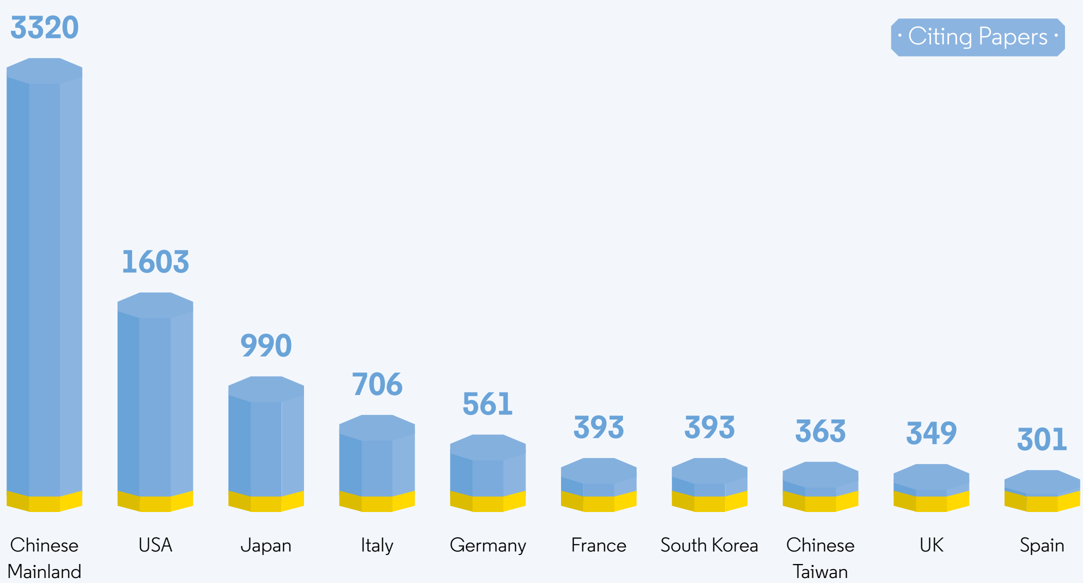


In terms of citing papers, the contribution rate from China is the highest, accounting for nearly half the total, significantly surpassing the second-place USA. Among the Top10 institutions producing citing papers, seven are in China. Noted universities in China, such as Sun Yat-sen University, Fudan University, Zhejiang University, and Peking Union Medical College/Chinese Academy of Medical Sciences, top the list, reflecting their active research and excellent development trend in systematic treatment of hepatocellular carcinoma.

Table 21: Top countries/regions and institutions producing citing papers in the Research Front "Targeted therapy or immunotherapy for unresectable hepatocellular carcinoma"

Country region Ranking	Country/ region	Citing Papers	Proportion
1	Chinese Mainland	3320	44.0%
2	USA	1603	21.2%
3	Japan	990	13.1%
4	Italy	706	9.4%
5	Germany	561	7.4%
6	France	393	5.2%
7	South Korea	393	5.2%
8	Chinese Taiwan	363	4.8%
9	UK	349	4.6%
10	Spain	301	4.0%

Institution Ranking	Institution	Affiliated Country/ region	Citing Papers	Proportion
1	Sun Yat Sen University	Chinese Mainland	358	4.7%
2	Fudan University	Chinese Mainland	318	4.2%
3	Zhejiang University	Chinese Mainland	252	3.3%
4	Chinese Academy of Medical Sciences - Peking Union Medical College	Chinese Mainland	224	3.0%
5	Harvard University	USA	198	2.6%
5	Kindai University	Japan	198	2.6%
7	Huazhong University of Science & Technology	Chinese Mainland	191	2.5%
8	National Institute of Health and Medical Research (INSERM)	France	182	2.4%
9	Chinese Academy of Sciences	Chinese Mainland	174	2.3%
10	Naval Medicine university	Chinese Mainland	163	2.2%



2. EMERGING RESEARCH FRONT

2.1 SUMMARY OF EMERGING RESEARCH FRONTS IN CLINICAL MEDICINE

The four emerging Research Fronts in clinical medicine, as Table 22 notes, are mainly concerned with "non-insulin hypoglycemic drugs for obesity or type 2 diabetes", "endovascular treatment of acute massive ischemic stroke", "monoclonal antibody drugs for plaque psoriasis", and "application of wearable ultrasound systems". Based on the CPT index, the front's development potential, and the judgment of science- and technology-information researchers, the front "Application of wearable ultrasound system" has ultimately been selected as the key focus for analysis.

Table 22: Emerging Research Fronts in clinical medicine

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Non-insulin hypoglycemic agents for obesity or type 2 diabetes	8	190	2023.0
2	Endovascular treatment of acute massive ischemic stroke	3	405	2022.7
3	Monoclonal antibody drugs for plaque psoriasis	15	318	2022.7
4	Application of wearable ultrasound systems	3	175	2022.7

2.2 KEY EMERGING RESEARCH FRONT – "Application of wearable ultrasound systema"

In recent years, with the improvement of living standards and the progress of science and technology, mobile healthcare has gradually emerged, and the advancements in fields such as new materials, integrated circuits, and AI have made it possible for medical devices to evolve towards miniaturization, portability, and wearability.

As a rapid, simple, non-invasive and non-radiation diagnostic tool, ultrasound technology has been widely used in the medical field since the mid-20th century. The wearable ultrasound system combined with wearable ultrasound technology can not only facilitate clinicians in evaluating the functions of tissues and organs and diagnose various diseases, but also in operating for extended periods. This allows healthcare providers to continuously monitor patients' health status and observe disease progression in real-time. Therefore, wearable ultrasound systems have an extremely important role and development prospect in clinical diagnosis and daily monitoring.

The emerging research front "Application of wearable ultrasound systems" include the development of bioadhesive ultrasound for long-term continuous imaging of different organs, the development of wearable cardiac ultrasound imager, and the monitoring effect of fully integrated wearable ultrasound system on deep tissues of moving objects. Interpretation of the pertinent literature suggests that the wearable ultrasound systems developed at this stage have the advantages of non-invasiveness, low power consumption, miniaturization, high penetration depth, and high resolution. This technology mainly relies on deep learning models and machine learning technology to continuously 3D image, monitor and evaluate the physiological signals of internal organs, including blood vessels, muscles, heart, gastrointestinal tract, diaphragm, and lung and deep tissues (such as central blood pressure, heart rate, and cardiac output). It does little harm to human skin, so it has a broad application prospect. It can become a portable diagnosis and monitoring tool for various diseases, provide important information about health and diseases, and make it possible to continuously monitor the deep tissue signals facing the medical Internet of Things. Its characteristics and development trends include: (1) Miniaturization and wireless, improving wearing comfort; (2) Smart medical care, introducing clinical needs to improve practicality; (3) Photoacoustic imaging, complementary and mutual inspection to expand the application scope; (4) AI diagnosis, greatly improving efficiency; (5) Advanced materials to achieve a dual breakthrough in mechanics and imaging; and (6) Compared with other medical imaging methods such as magnetic resonance imaging(MRI) and computed tomography(CT), it is safer, cheaper, and more widely used.

06

BIOLOGICAL SCIENCES

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN BIOLOGICAL SCIENCES

The Top 10 Research Fronts in biological sciences include prime editing technology, protein structure prediction using artificial intelligence (AI), cell communication analysis technology, cell death, organoids, predictive biomarkers for disease and mortality risk, bacteriophage therapy, and other research.

Among these specialty areas, genome editing technology has consistently been a prominent area of research in biological sciences. In recent years, genome editing technology has also been constantly updated and refined. Prime editing technology was identified as a hot Research Front in 2023 and has been selected again in 2024. AI tools, such as AlphaFold, have revolutionized protein structure prediction, marking a significant technological leap and causing a paradigm shift in the field of biology. It became an emerging Research Front in the field of biological sciences in 2022, a hot Research Front in 2023, and continues be a hot front in this latest update.

In 2023, cell communication analysis technology was introduced as an auxiliary technology for single-cell sequencing analysis and was recognized as a hot Research Front – a distinction it maintains in 2024.

Cell death has also been a research hotspot in recent years, with Cuproptosis becoming an emerging front in 2023 and earning selection as a hot front in 2024. Additionally, research on pyroptosis is also rapidly gaining popularity; the related hot front in 2024 is “Constructing a cancer prognostic model based on pyroptosis genes”. Another emerging Research Front in 2024 is “Key effector factors of pyroptosis - GSDMs family”.

As a new type of model, organoids show great potential in the field of scientific research. In 2024, two hot fronts on organoids were identified. “A model of functional human brain organoids,” focused on research into human brain organoids, while “3D bioprinting” showcases exploration of organoids such as those of the heart, liver, and bones.

In the area of predictive biomarkers for disease and death risk, two newly selected hot Research Fronts have distinguished themselves in 2024, including “Tumor tertiary lymphoid structures - tumor predictive markers” and “Epigenetic clock”. Bacteriophage therapy, as an innovative approach to combat antibiotic resistant bacteria, also was recognized as a hot front in 2024.

Table 23: Top10 Research Fronts in biological sciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Cuproptosis	30	3832	2021.8
2	Artificial intelligence predicts protein structure	5	16580	2021.2
3	Tumor tertiary lymphoid structures - tumor predictive markers	15	4907	2020.6
4	Cell communication analysis technology	5	2197	2020.4
5	3D bioprinting	20	5304	2020.3
6	Prime editing technology	29	7510	2020.2
7	Constructing a cancer prognostic model based on Pyroptosis genes	6	1826	2020.2
8	Bacteriophage therapy	11	2740	2020.0
9	Epigenetic clock	13	4424	2019.9
10	A model of functional human brain organoids	29	6581	2019.6

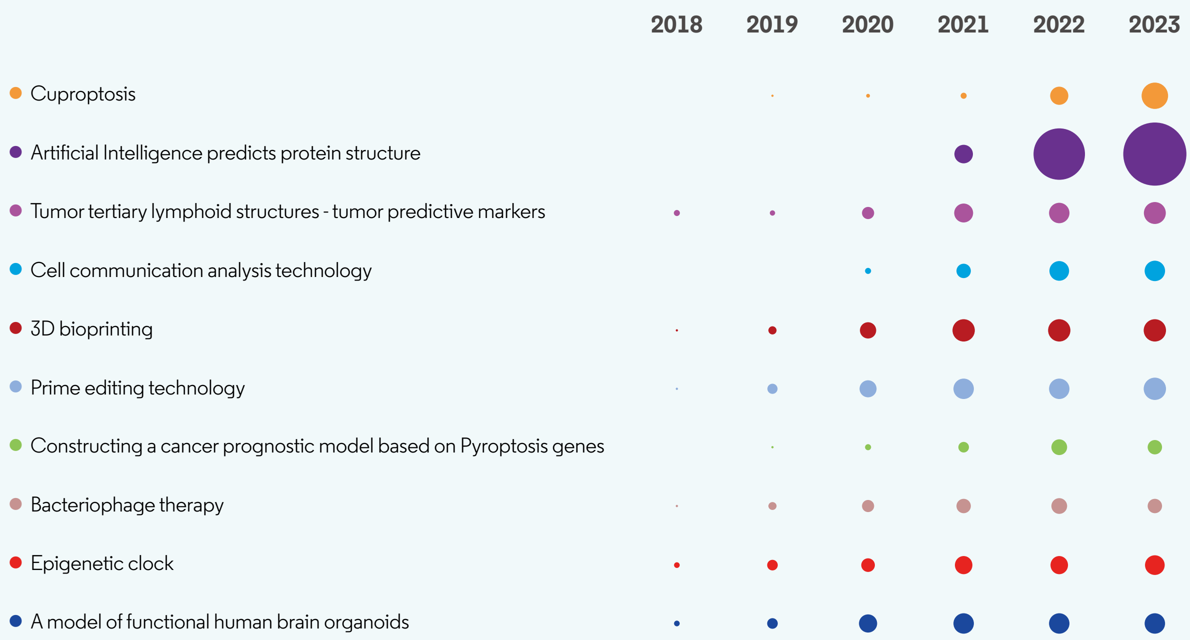


Figure 13: Citing papers for the Top 10 Research Fronts in biological sciences

1.2 KEY HOT RESEARCH FRONT – "Epigenetic clock"

Aging is a complex process characterized by various changes at the cellular, subcellular, and nuclear levels, in which cells irreversibly stop dividing and enter a state of permanent growth arrest without undergoing cell death. Common biomarkers applied to measure physiological age include DNA methylation, telomere length, transcriptomics data, proteomics data, and metabolomics data. Among these, DNA methylation age (DNAmAge) is considered one of the most reliable indicators currently available. Meanwhile, DNA methylation is also the most widely studied epigenetic phenomenon, playing a crucial role in growth, development, and aging. At present, DNA methylation patterns have been widely used as an indicator of biological age, known as the epigenetic clock.

The epigenetic clock, based on DNA methylation, is a powerful biomarker, which has been developed to track aging, clinical trials, and personal health applications in population research. It aims to determine the biological age of the body and can more accurately predict age-related morbidity and mortality in humans, as well as other aspects of bodily health. The epigenetic clock has ushered in a new era of molecular research in the field of aging. There are three generation epigenetic clocks. The first generation includes the Horvath clock (2013) and Hannum clock (2013); the second generation consists of PhenoAge (2018) and Grimage (2019); and the third includes DunedinPoAm (2020) and DunedinPACE (2022). The 13 core papers underlying this Research Front include reviews of the first-generation clock, as well as related studies on the proposal and comparison of the second and third generations.

The first-generation Horvath clock and Hannum clock were evaluated based on actual age, so they were also designated as age clocks. The second generation DNAm PhenoAge and DNAm GrimAge are predictive models based on aging markers and were therefore classified as mortality clocks. The third generation, DunedinPoAm and DunedinPACE, employs longitudinal phenotype training data to measure the speed of biological aging and can be defined as the aging rate clock. The third-generation epigenetic clock demonstrates higher sensitivity and reliability.

The latest research trend in topics

related to the epigenetic clock is the continuous improvement of prediction accuracy, the ongoing expansion of species coverage, and the establishment of a comprehensive pattern of cell level → multi tissue → multi organ → multi clock integration platform. The continuous deepening of various studies related to the epigenetic clock make it plain that the technology is becoming a powerful tool for studying the health, development, and aging of the entire life cycle. Indeed, the current progress hints of even more possibilities and endless potential waiting to be discovered.

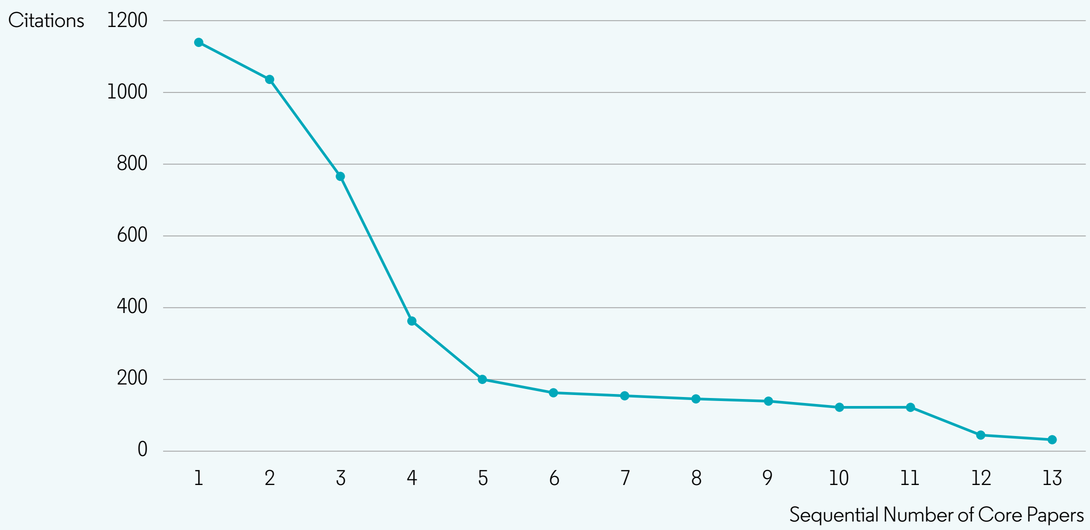


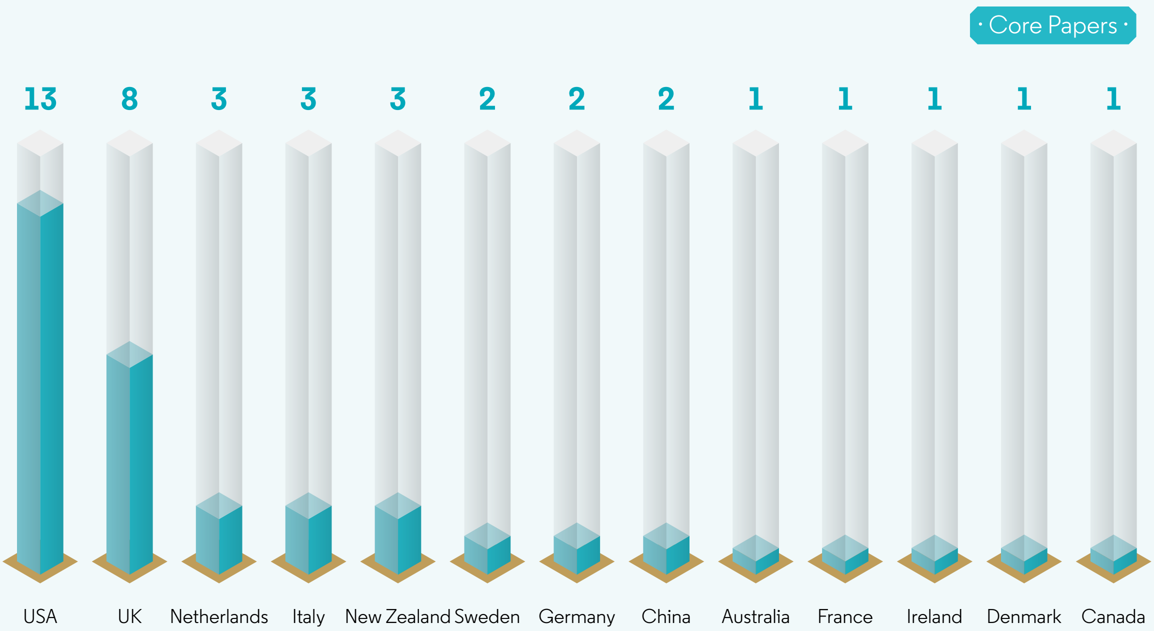
Figure 14: Citation frequency distribution curve of core papers in the Research Front "Epigenetic clock"

From the perspective of the countries and institutions that produce core papers, the USA leads with contributions to all 13 core papers in this front. The UK contributed eight core papers, while China was involved in two. On the list of top institutions, seven are based in the USA, with Columbia University being the most prolific contributor, accounting for over half of the core papers. King's College London and the University of California, Los Angeles rank 2nd, followed by Duke University (Table 24).

Table 24: Top countries and institutions producing core papers in the Research Front "Epigenetic clock"

Country Ranking	Country	Core Papers	Proportion
1	USA	13	100.0%
2	UK	8	61.5%
3	Netherlands	3	23.1%
3	Italy	3	23.1%
3	New Zealand	3	23.1%
6	Sweden	2	15.4%
6	Germany	2	15.4%
6	China	2	15.4%
9	Australia	1	7.7%
9	France	1	7.7%
9	Ireland	1	7.7%
9	Denmark	1	7.7%
9	Canada	1	7.7%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Columbia University	USA	7	53.8%
2	Kings College London	UK	5	38.5%
2	University of California Los Angeles	USA	5	38.5%
4	Duke University	USA	4	30.8%
5	University of Otago	New Zealand	3	23.1%
5	Harvard University	USA	3	23.1%
5	Yale University	USA	3	23.1%
5	University of North Carolina Chapel Hill	USA	3	23.1%
5	University of Exeter	UK	3	23.1%
5	National Institutes of Health (NIH)	USA	3	23.1%

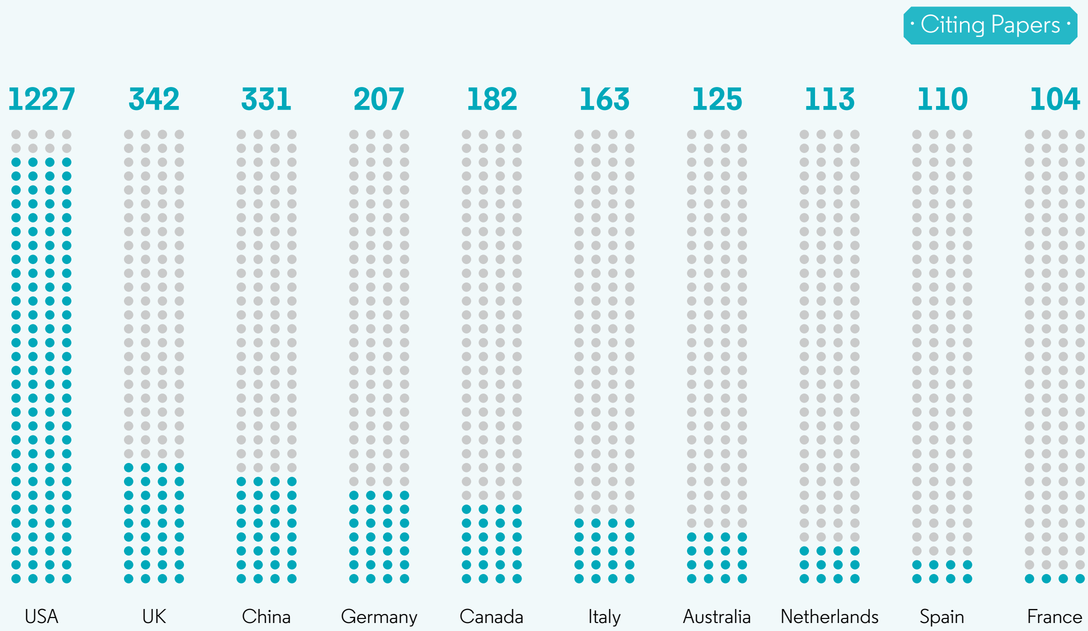


From the distribution of the citing papers (Table 25), the USA is the most active country, participating in 1,227 citing papers, accounting for over half of the total, and far exceeding other countries. The UK and China actively follow up on this front, participating in 342 and 331 citing papers, respectively. Among the Top 10 institutions producing citing papers, eight are based in the USA, with the remaining two being the Karolinska Institute in Sweden and the Helmholtz Association in Germany.

Table 25: Top countries and institutions producing citing papers in the Research Front "Epigenetic clock"

Country Ranking	Country	Citing Papers	Proportion
1	USA	1227	53.3%
2	UK	342	14.9%
3	China	331	14.4%
4	Germany	207	9.0%
5	Canada	182	7.9%
6	Italy	163	7.1%
7	Australia	125	5.4%
8	Netherlands	113	4.9%
9	Spain	110	4.8%
10	France	104	4.5%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	University of California Los Angeles	USA	175	7.6%
2	Harvard University	USA	174	7.6%
3	National Institutes of Health (NIH)	USA	131	5.7%
4	Columbia University	USA	119	5.2%
5	Yale University	USA	81	3.5%
6	Karolinska Institutet	Sweden	74	3.2%
6	University of North Carolina Chapel Hill	USA	74	3.2%
8	Helmholtz Association	Germany	68	3.0%
8	Stanford University	USA	68	3.0%
10	Northwestern University	USA	64	2.8%



1.3 KEY HOT RESARCH FRONT – "A model of functional human brain organoids"

Organoids are micro-organ clusters formed by 3D culturing cells with stemness potential in vitro, forming a collection of multiple specific cell types. They can reproduce the three-dimensional structure and physiological functions of real organs in vitro. The ability of organoids to differentiate, self-organize, and form unique, complex, biologically relevant structures makes them an ideal model for in vitro development, disease pathogenesis, and drug screening platforms.

A brain organoid is a three-dimensional neural tissue that is cultured in vitro, with a structure similar to that of the human brain. Human-brain organoids have demonstrated significant advantages over animal models in uncovering the genetic basis of human neurodevelopment and neuropsychiatric disorders.

The 29 core papers forming the foundation of this hot front report on the cultivation scheme of human-brain organoids that simulate the development of different brain regions, including the development of the cortex, midbrain, and retina. Meanwhile, research has also confirmed that human-brain organoids can effectively simulate in vivo processes such as neurogenesis, neuronal migration, cortical stratification, and neural circuit establishment. Moreover, work described in this Research Front has successfully constructed human-brain organoids with vascular-like structures, as well as those with microglial cell development and function.

Other studies have centered on the construction of multi-system synergistic human-brain organoids, achieving breakthrough results in solving the so-called "three major difficulties" in this specialty: a lack of vascularized structures, lack of immune cells, and low degree of organ systematization in human brain organoids, thereby promoting the development of human-brain organoid research.

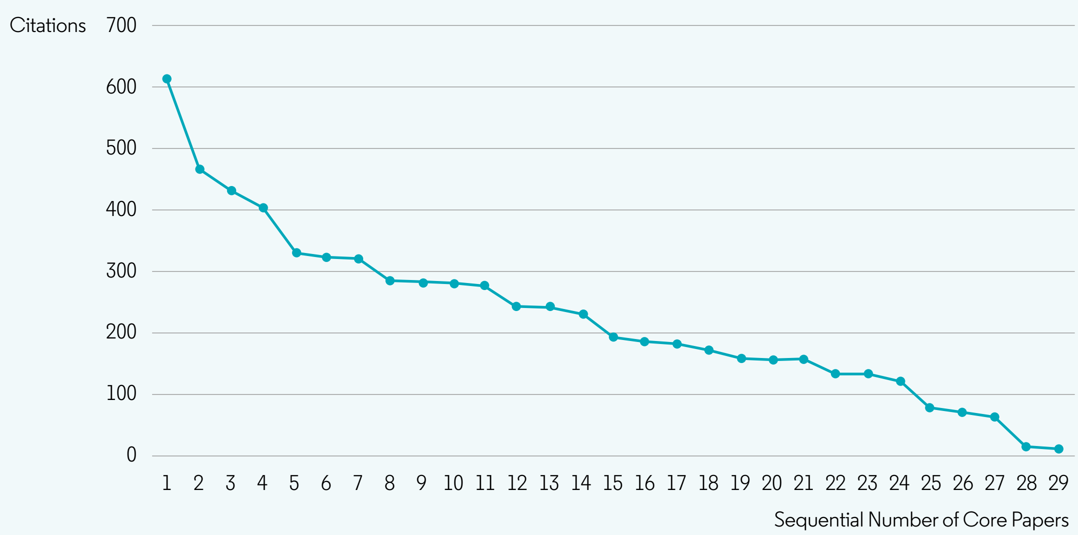


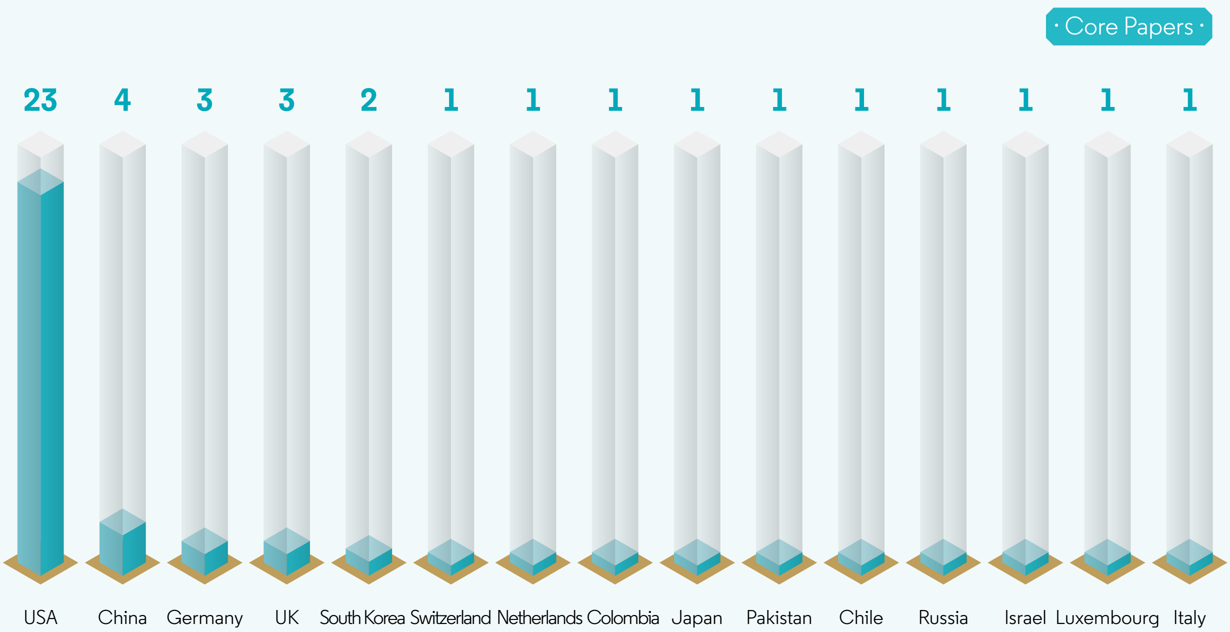
Figure 15: Citation frequency distribution curve of core papers in the Research Front "A model of functional human brain organoids"

As for the distribution of core papers: the USA contributes 79.3% of foundational literature in this Research Front, demonstrating a clear and absolute advantage. China ranks second in core paper output, but only accounts for 13.8%, showing a significant gap compared to the USA. 10 of the top-producing institutions (including 12 institutions tied for the same rank) are from the USA. Stanford University participated in publishing six core papers, ranking 1st, and the Chinese Academy of Sciences ranks 2nd.

Table 26: Top countries and institutions producing core papers in the Research Front "A model of functional human brain organoids"

Country Ranking	Country	Core Papers	Proportion
1	USA	23	79.3%
2	China	4	13.8%
3	Germany	3	10.3%
3	UK	3	10.3%
5	South Korea	2	6.9%
6	Switzerland	1	3.4%
6	Netherlands	1	3.4%
6	Colombia	1	3.4%
6	Japan	1	3.4%
6	Pakistan	1	3.4%
6	Chile	1	3.4%
6	Russia	1	3.4%
6	Israel	1	3.4%
6	Luxembourg	1	3.4%
6	Italy	1	3.4%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Stanford University	USA	6	20.7%
2	Chinese Academy of Sciences	China	4	13.8%
3	Harvard University	USA	3	10.3%
3	University of California Los Angeles	USA	3	10.3%
3	University of Pennsylvania	USA	3	10.3%
3	University of California San Diego	USA	3	10.3%
7	Massachusetts Institute of Technology (MIT)	USA	2	6.9%
7	University of California San Francisco	USA	2	6.9%
7	University of California Santa Cruz	USA	2	6.9%
7	Salk Institute	USA	2	6.9%
7	Max Planck Society	Germany	2	6.9%
7	Johns Hopkins University	USA	2	6.9%

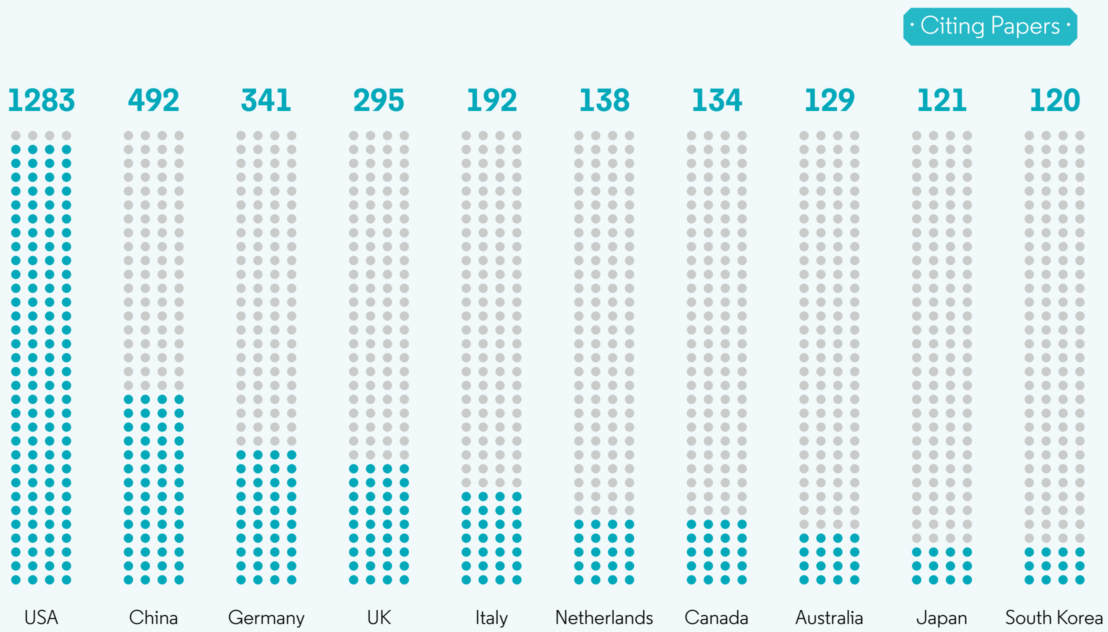


Analysis of the citing papers indicates that the USA remains the most active in this Research Front, contributing 1,283 papers, followed by China and its 492 citing papers (Table 27). Among the Top 10 institutions, seven are based in the USA, while Germany is host to two, and China claims one. The institution with the largest number of citing papers is Harvard University. The two German institutions are the Max Planck Society and the Helmholtz Association, ranking 6th and 8th respectively. The Chinese Academy of Sciences ranks 7th, with a total of 76 citing papers.

Table 27: Top countries and institutions producing citing papers in the Research Front "A model of functional human brain organoids"

Country Ranking	Country	Citing Papers	Proportion
1	USA	1283	43.4%
2	China	492	16.7%
3	Germany	314	10.6%
4	UK	295	10.0%
5	Italy	192	6.5%
6	Netherlands	138	4.7%
7	Canada	134	4.5%
8	Australia	129	4.4%
9	Japan	121	4.1%
10	South Korea	120	4.1%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Harvard University	USA	176	6.0%
2	University of California San Diego	USA	97	3.3%
3	Massachusetts Institute of Technology (MIT)	USA	90	3.0%
4	Stanford University	USA	87	2.9%
5	University of California San Francisco	USA	84	2.8%
6	Max Planck Society	Germany	79	2.7%
7	Chinese Academy of Sciences	China	76	2.6%
8	Helmholtz Association	Germany	70	2.4%
9	Broad Institute	USA	66	2.2%
9	University of Pennsylvania	USA	66	2.2%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN BIOLOGICAL SCIENCES

Four studies in biological sciences have been identified as emerging fronts, with the main research topics including “TRACERx study provides a detailed explanation of the progression and metastasis pathways of lung cancer”, “Key effector factors of pyroptosis - GSDMs family”, “Efficient CRISPR-CAS12A promoter editing system”, and “Alpha Synuclein as a biomarker for PD Prediction”. Based on the comprehensive CPT indicators (please refer to the methodology section for details), the development potential of these Research Fronts, and the judgment of science and technology information researchers, the front “Key effector factors of pyroptosis - GSDMs family” was ultimately selected for closer examination.

Table 28: Emerging Research Fronts in biological sciences

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	TRACERx study provides a detailed explanation of the progression and metastasis pathways of lung cancer	7	163	2023.0
2	Key effector factors of pyroptosis - GSDMs family	8	174	2022.9
3	Efficient CRISPR-CAS12A promoter editing system	7	153	2022.9
4	Alpha Synuclein as a biomarker for PD Prediction	5	165	2022.6

2.2 KEY EMERGING RESARCH FRONT – “Key effector factors of pyroptosis - GSDMs family”

Pyroptosis is a lytic programmed cell death caused by the activation of gasdermin (GSDM) protein by upstream signals, which releases its N-terminal domain and punctures the cell membrane, exhibiting highly pro-inflammatory immunological features.

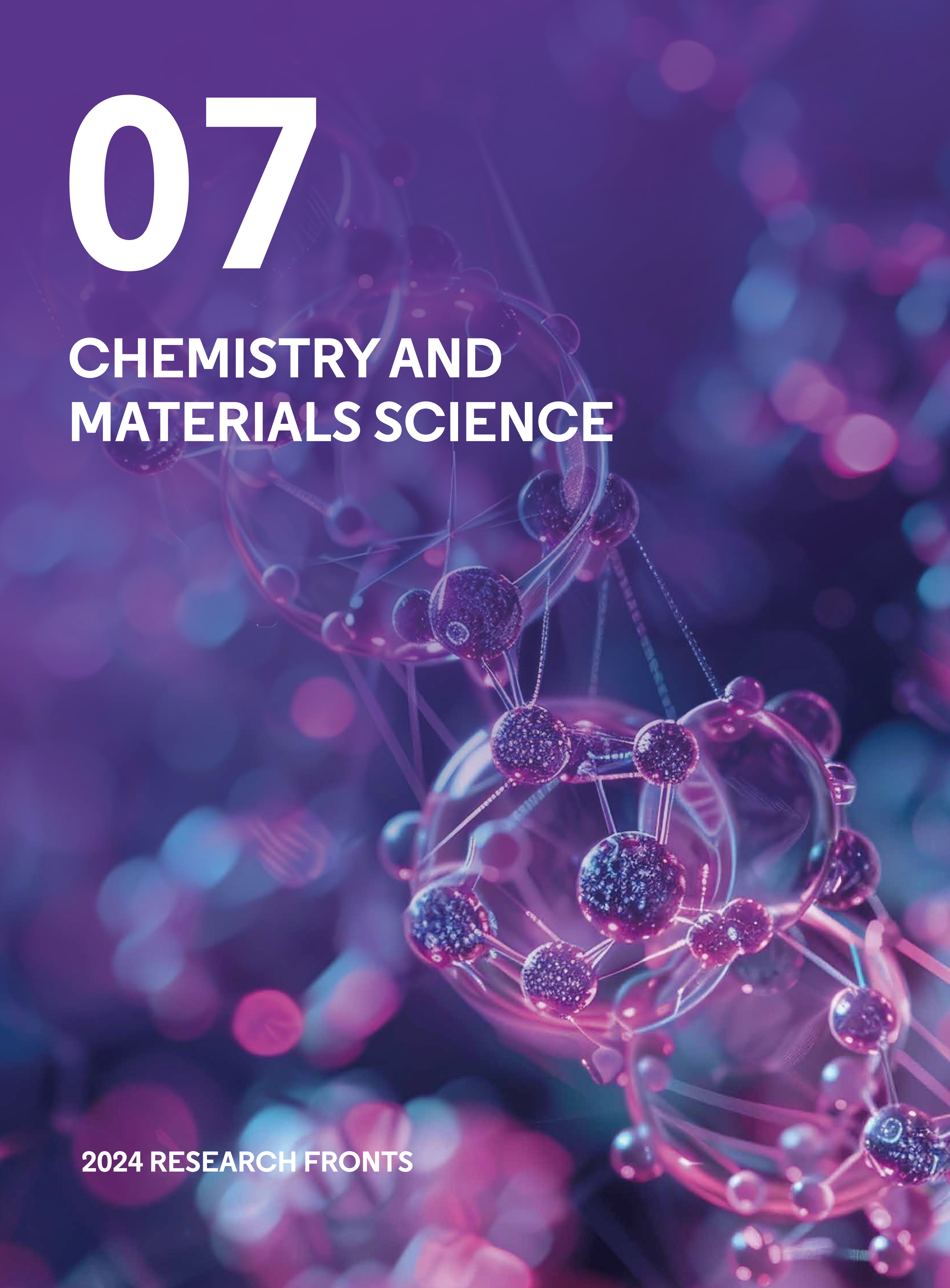
The human GSDM protein family consists of six members, including GSDMA, GSDMB, GSDMC, GSDMD, GSDME (also known as DFNA5), and DFNB59 (also known as PJVK). The N-terminal fragment of GSDM A/B/C/D/E exhibits membrane perforation activity. GSDMD-mediated pyroptosis plays an important role in the innate immune response against pathogenic infections, while other GSDMs (including GSDMB- and GSDME-mediated pyroptosis) play important roles in anti-tumor immunity. In recent years, some studies (including a core paper published in 2022) have questioned the focal failure function of GSDMB. Research has shown that unlike other GSDM proteins, GSDMB does not induce pyroptosis, especially in epithelial cells, but it maintains gastrointestinal health, indicating that these proteases exhibit an inhibitory mechanism of pyroptosis.

Subsequently, several core papers published in 2023 reported that GSDMB has at least five alternative splicing isoforms, designated GSDMB1-5, which are also targeted by IpaH7.8 but exhibit vastly different pyroptosis activities. When the N-terminal domain of GSDMB is cleaved and released through Granzyme-A, it triggers cancer cell death, but uncut GSDMB promotes various pro-tumor effects, including invasion, metastasis, and drug resistance. Previous studies have used different isomers. This thusly explains the seemingly conflicting results in the literature regarding the perforation activity of GSDMB NT membranes. These studies suggest that different GSDMB alternative splicing isoforms play distinct roles in cytotoxic lymphocyte mediated cell death and anti-tumor immunity and reveal a novel mechanism by which tumor cells can evade cell death by manipulating GSDMB alternative splicing. The alternative splicing of GSDMB is a possible new drug target, and manipulating the alternative splicing of GSDMB in tumor cells to upregulate the expression of toxic GSDMB isoforms may enhance anti-tumor immune response.

In summary, these studies are of great significance for understanding the complex role of GSDMB subtypes in cancer or other pathology, as well as for the future design of GSDMB targeted therapies.

07

CHEMISTRY AND MATERIALS SCIENCE



1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN CHEMISTRY AND MATERIALS SCIENCE

The Top 10 Research Fronts in chemistry and materials science in 2024 spotlight specialty areas in energy chemistry, catalysis and surfaces/interfaces, and materials chemistry. In the field of energy chemistry, four Research Fronts have been selected, examining solar cells, fuel cells, flow batteries, and metal ion batteries. In the field of catalysis and surfaces/interfaces, three Research Fronts have been identified; respectively, these treat transition metal catalysis, electrocatalysis, and adsorption. Two Research Fronts in the field of materials chemistry are highlighted, both concerning luminescent materials – namely, carbon dots-based luminescent materials and organic light-emitting materials with narrowband emission. Also making the Top 10 is a Research Front concerning lanthanide-based single-molecule magnets.

Table 29 Top10 Research Fronts in chemistry and materials science

Rank	Hot Research Fronts	Core papers	Citations	Mean Year of Core Papers
1	Carbon dots-based luminescent materials	36	4092	2021.1
2	Sb_2Se_3 thin-film solar cells	15	2241	2021.1
3	Electrocatalysts for oxygen evolution in acidic media	32	6134	2020.4
4	Organic light-emitting materials with narrowband emission	23	4243	2020.4
5	Transition metal-catalyzed difunctionalization of alkenes	36	6370	2020.0
6	Anion exchange membrane water electrolyzers and fuel cells	26	6016	2020.0
7	Adsorption-based atmospheric water harvesting	27	5174	2020.0
8	Redox flow batteries	23	4118	2020.0
9	Design of dendrite-free zinc anodes for aqueous zinc-ion batteries	41	19689	2019.8
10	Lanthanide-based single-molecule magnets	20	5090	2019.8

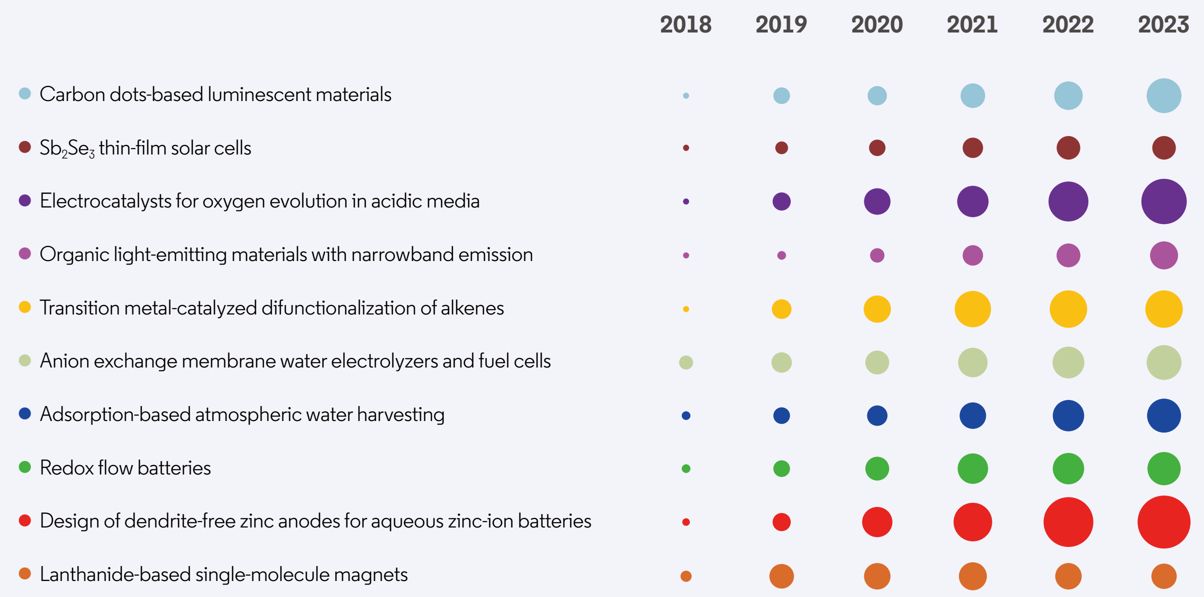


Figure 16: Citing papers of the Top 10 Research Fronts in chemistry and materials science

1.2 KEY HOT RESEARCH FRONT – "Design of dendrite-free zinc anodes for aqueous zinc-ion batteries"

Aqueous zinc-ion batteries (ZIBs) have attracted increased attention as an energy storage solution for large-scale applications, owing to the advantageous characteristics of Zn anodes, which include high theoretical capacity (820 mA h g^{-1}), low redox potential (−0.762 V relative to the standard hydrogen electrode), high availability, environmental friendliness, and inherent safety. However, the zinc metal anode has serious inherent issues with dendritic growth, zinc corrosion, and hydrogen evolution. In particular, the growth of Zn dendrites not only leads to internal short circuits by penetrating the separator but also promotes side reactions such as corrosion and hydrogen evolution, which are major bottlenecks impeding the development of next-generation ZIBs.

The 41 highly cited papers constituting the core of this Research Front propose several strategies to prohibit the Zn dendrite growth, including protective layer coating, structural design of anodes, and electrolyte composition optimization (e.g., adoption of electrolyte additives, deep eutectic electrolytes, or high concentration electrolytes). The most-cited core paper is coauthored by researchers at the University of Maryland, the US Army Research Laboratory, and the National Institute of Standards and Technology (USA). In this paper, the researchers designed an aqueous electrolyte composed of high-concentration zinc ions and lithium salts. This mixture, which is neutral in pH and capable of retaining water in an open atmosphere, promotes dendrite-free plating/stripping of Zn at nearly 100% coulombic efficiency and brings unprecedented reversibility to aqueous Zn batteries with either $LiMn_2O_4$ or O_2 cathodes.

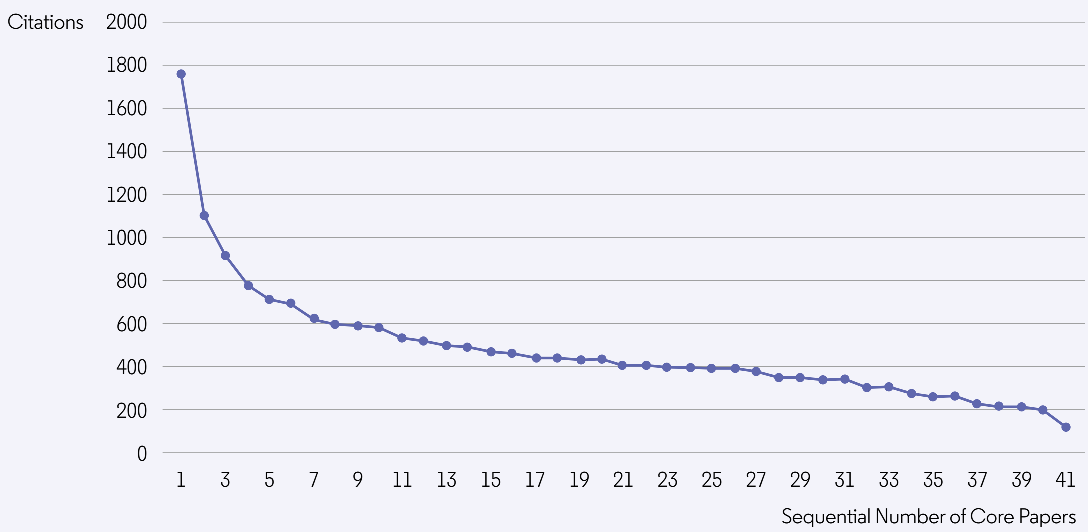


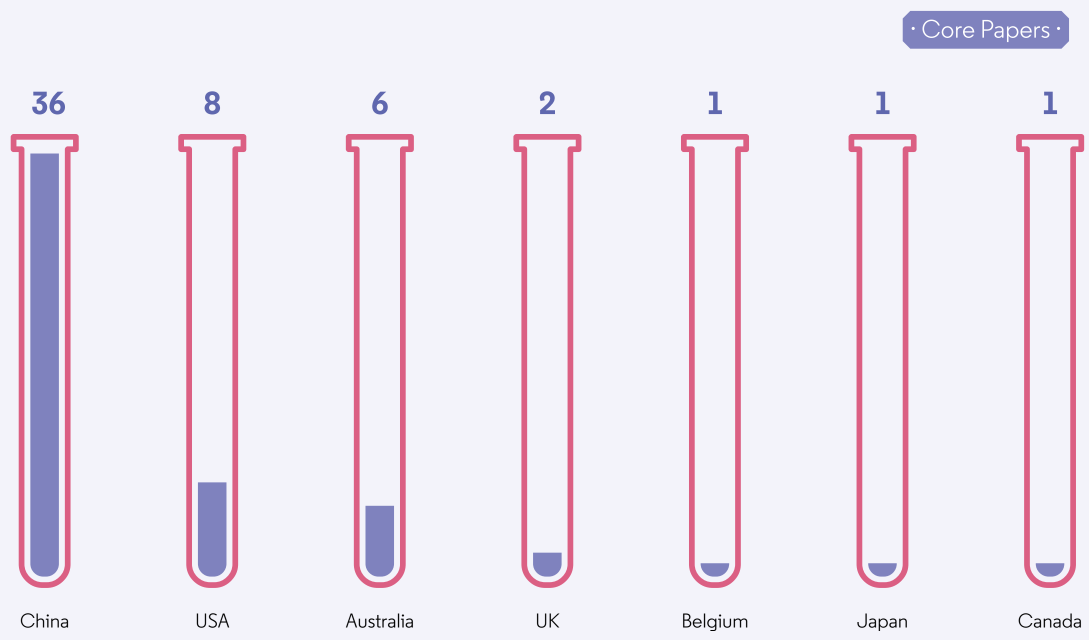
Figure17: Citation frequency distribution curve of core papers in the Research Front "Design of dendrite-free zinc anodes for aqueous zinc-ion batteries"

As shown in Table 30, China has contributed 36 core papers, significantly more than any other country on the list. The USA and Australia rank 2nd and 3rd, respectively. The top 10 institutions producing core papers include eight China-based institutions, with the Chinese Academy of Sciences ranking 1st with seven papers.

Table 30 Top countries and institutions producing core papers in the Research Front "Design of dendrite-free zinc anodes for aqueous zinc-ion batteries"

Country Ranking	Country	Core Papers	Proportion
1	China	36	87.8%
2	USA	8	19.5%
3	Australia	6	14.6%
4	UK	2	4.9%
5	Belgium	1	2.4%
5	Japan	1	2.4%
5	Canada	1	2.4%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Chinese Academy of Sciences	China	7	17.1%
2	Central South University	China	6	14.6%
3	City University of Hong Kong	China	4	9.8%
3	University of Wollongong	Australia	4	9.8%
3	Shanghai University	China	4	9.8%
6	Fudan University	China	3	7.3%
6	Nankai University	China	3	7.3%
6	Sun Yat Sen University	China	3	7.3%
6	Tianjin University	China	3	7.3%
6	University of Maryland	USA	3	7.3%

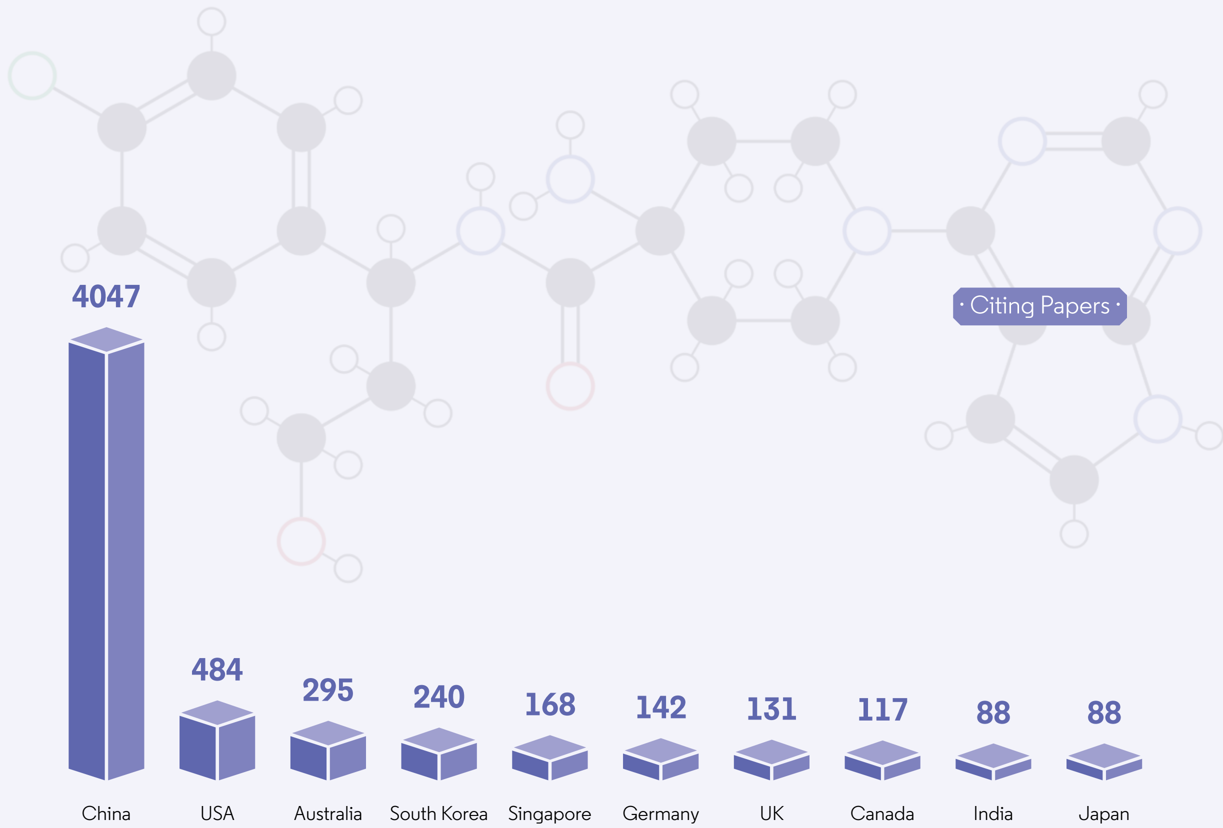


As shown in Table 31, China has published the greatest number of citing papers in this front, far ahead of other countries on the list. The USA and Australia come in 2nd and 3rd, respectively. China is home to all the Top 10 institutions producing citing papers, a sign of the country's high level of attention and ongoing commitment to this specialty area.

Table 31: Top countries and institutions producing citing papers in the Research Front "Design of dendrite-free zinc anodes for aqueous zinc-ion batteries"

Country Ranking	Country	Citing Papers	Proportion
1	China	4047	82.8%
2	USA	484	9.9%
3	Australia	295	6.0%
4	South Korea	240	4.9%
5	Singapore	168	3.4%
6	Germany	142	2.9%
7	UK	131	2.7%
8	Canada	117	2.4%
9	India	88	1.8%
9	Japan	88	1.8%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	678	13.9%
2	Central South University	China	306	6.3%
3	University of Science and Technology of China	China	234	4.8%
4	City University of Hong Kong	China	198	4.1%
5	Nankai University	China	168	3.4%
6	Tsinghua University	China	142	2.9%
6	Zhengzhou University	China	142	2.9%
8	Hunan University	China	133	2.7%
9	Harbin Institute of Technology	China	124	2.5%
10	Fudan University	China	119	2.4%



1.3 KEY HOT RESARCH FRONT – "Adsorption-based atmospheric water harvesting"

Water is the source of life; however, two-thirds of the world's population suffers from water scarcity. Moreover, many countries facing this scarcity are landlocked, making saltwater desalination impractical in most cases. Although a substantial amount of water is present in the form of vapor in the atmosphere, harvesting this water by dewing technology can be energy-intensive and impractical, especially in areas with relatively low humidity. In contrast, solar-thermal-driven, sorption-based atmospheric water harvesting, which enables vapor capture at low relative-humidity conditions, has been considered a promising way to address water scarcity in arid regions, land-locked areas, and remote communities.

The 27 highly cited papers constituting the core of this Research Front focus on improving the production efficiency of adsorption-based atmospheric water harvesting in terms of adsorbent material design and device structure design, with the majority emphasizing the former. The materials proposed for water harvesting can be categorized as metal–organic frameworks (MOFs), covalent organic frameworks, polymer hydrogels, core-shell nanocomposites, among others. The four most highly cited core papers are from Omar M. Yaghi's group at the University of California (UC), Berkeley in the USA. In the most-cited report, Yaghi discusses chemical and structural factors crucial for the design of MOFs for water adsorption; presents water adsorption mechanisms in MOFs alongside strategies for fine-tuning their adsorption behavior; suggests a method for the selection of promising MOFs concerning water harvesting from air; and outlines design concepts for next-generation MOFs for application in passive adsorption-based water-harvesting devices.

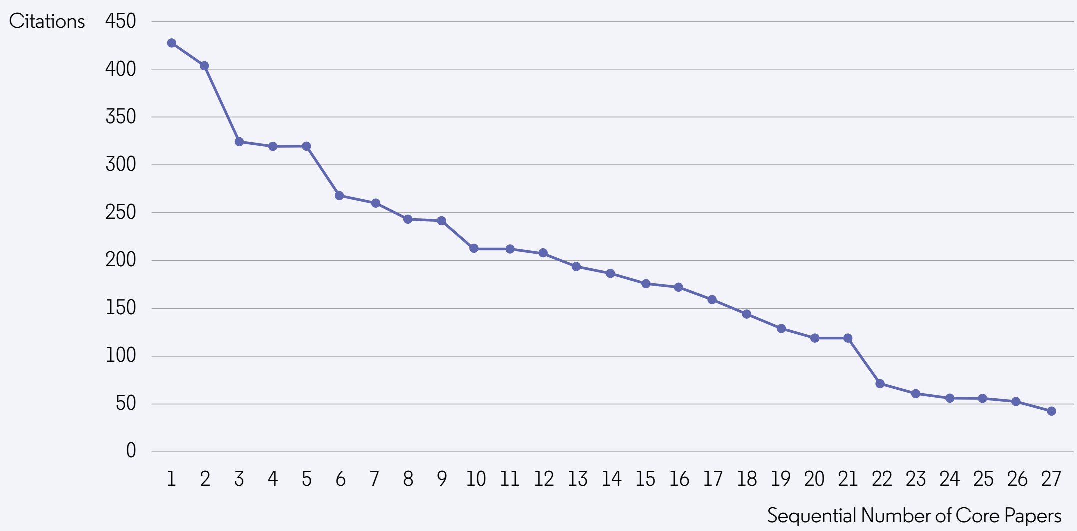


Figure18: Citation frequency distribution curve of core papers in the Research Front "Adsorption-based atmospheric water harvesting"

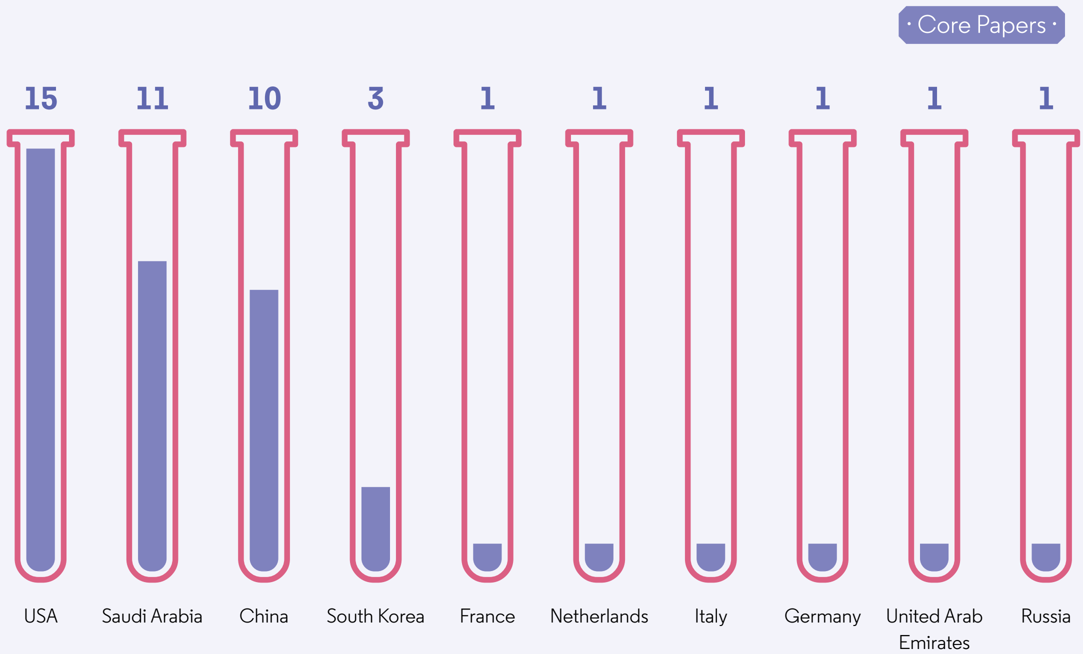
As shown in Table 32, the 27 core papers come from 10 countries, indicating widespread attention to the significance of this Research Front. Furthermore, the inclusion of two arid countries on the list highlights the significant practical relevance of this technology to those regions. The USA has contributed 15 core papers, ranking 1st, with UC Berkeley, Lawrence Berkeley National Laboratory, the University of Texas at Austin, and MIT ranking 1st, 3rd, 4th, and 7th, respectively, on the list of top 10 institutions producing core papers. Saudi Arabia ranks 2nd with 11 core papers – however, seven of them derive from the collaboration between King Abdulaziz City for Science and Technology (Saudi

Arabia) and UC Berkeley (USA). As a result, King Abdulaziz City for Science and Technology ranks 2nd in the top 10 institutional listings. China ranks in 3rd place with 10 core papers. Four of these come from Shanghai Jiao Tong University, which shares the fourth position in the institutional rankings with the University of Texas at Austin (USA) and King Abdullah University of Science & Technology.

Table 32 Top countries and institutions producing core papers in the Research Front "Adsorption-based atmospheric water harvesting"

Country Ranking	Country	Core Papers	Proportion
1	USA	15	55.6%
2	Saudi Arabia	11	40.7%
3	China	10	37.0%
4	South Korea	3	11.1%
5	France	1	3.7%
5	Netherlands	1	3.7%
5	Italy	1	3.7%
5	Germany	1	3.7%
5	United Arab Emirates	1	3.7%
5	Russia	1	3.7%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of California Berkeley	USA	9	33.3%
2	King Abdulaziz City for Science and Technology	Saudi Arabia	7	25.9%
3	Lawrence Berkeley National Laboratory	USA	5	18.5%
4	University of Texas Austin	USA	4	14.8%
4	Shanghai Jiao Tong University	China	4	14.8%
4	King Abdullah University of Science & Technology	Saudi Arabia	4	14.8%
7	Massachusetts Institute of Technology (MIT)	USA	3	11.1%
8	Korea Institute of Science and Technology	South Korea	2	7.4%
8	Hong Kong Polytechnic University	China	2	7.4%
8	University of Utah	USA	2	7.4%

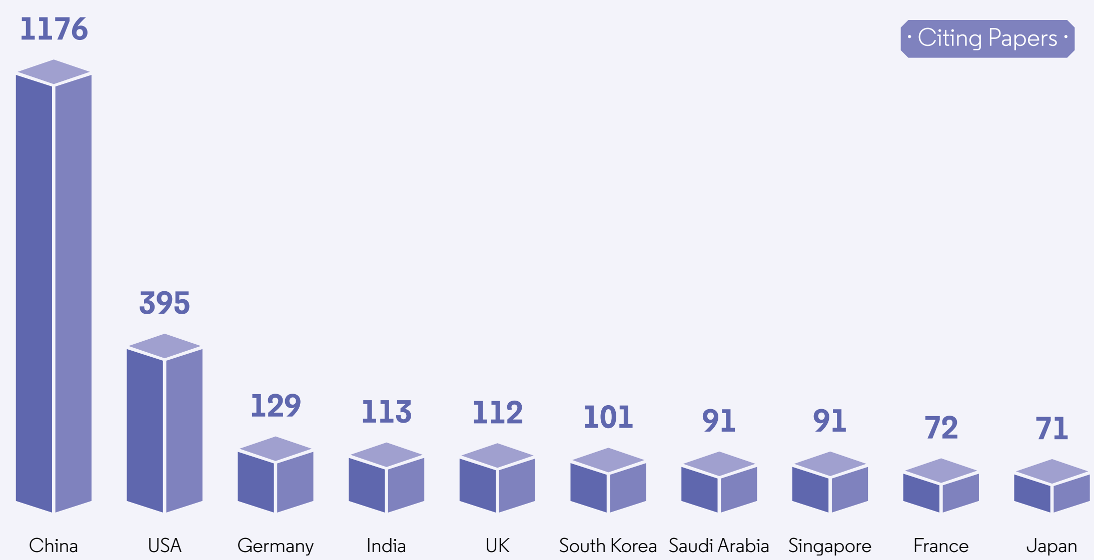


As shown in Table 33, China significantly surpasses other countries in total output of citing papers, reflecting the nation's close attention to this research direction. The USA and Germany follow at 2nd and 3rd place, respectively. Five of the Top 10 institutions producing citing papers are based in China, with the Chinese Academy of Sciences coming in 1st. The USA is home to two institutions, while Singapore, France, and Saudi Arabia each claim one.

Table 33 Top countries and institutions producing citing papers in the Research Front "Adsorption-based atmospheric water harvesting"

Country Ranking	Country	Citing Papers	Proportion
1	China	1176	54.1%
2	USA	395	18.2%
3	Germany	129	5.9%
4	India	113	5.2%
5	UK	112	5.2%
6	South Korea	101	4.6%
7	Saudi Arabia	91	4.2%
7	Singapore	91	4.2%
9	France	72	3.3%
10	Japan	71	3.3%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	155	7.1%
2	Shanghai Jiao Tong University	China	107	4.9%
3	National University of Singapore	Singapore	65	3.0%
4	Zhejiang University	China	64	2.9%
5	National Center for Scientific Research of France	France	63	2.9%
6	Huazhong University of Science & Technology	China	43	2.0%
6	University of California Berkeley	USA	43	2.0%
8	King Abdullah University of Science & Technology	Saudi Arabia	41	1.9%
9	Northwestern University	USA	39	1.8%
9	Tianjin University	China	39	1.8%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN CHEMISTRY AND MATERIALS SCIENCE

Three fronts have been selected as the emerging Research Fronts in the field of chemistry and materials science (Table 34), representing three areas: organic solar cells, organic transistors, and lithium metal batteries.

Table 34: Emerging Research Fronts in chemistry and materials science

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Small molecule acceptors for highly efficient organic solar cells	8	252	2022.8
2	Organic electrochemical transistors	6	239	2022.7
3	Solid polymer electrolytes for lithium metal batteries	9	336	2022.6

2.2 KEY EMERGING RESEARCH FRONT – "Organic electrochemical transistors"

Organic electrochemical transistors (OECTs), which are based on mixed ionic–electronic organic conductor components, offer advantages such as high ion sensitivity, fast switching, low driving voltages, high transconductances, and good biocompatibility. They harbor promising applications in areas that include logic circuits, sensor devices, health monitoring, and bioelectronic systems. The six core papers of this emerging front come from four countries: China, Sweden, the USA, and Saudi Arabia. The research includes the preparation and characterization of organic electrochemical transistors, as well as their applications in sensing, artificial pulse neurons, and logic circuits. The most-cited paper is coauthored by researchers from Linköping University in Sweden and other Swedish institutions.

In the paper, researchers report the organic electrochemical neurons (OECNs) with ion-modulated spiking, based on all printed complementary organic electrochemical transistors. They demonstrate facile bio-integration of OECNs with the Venus Flytrap plant to induce lobe closure in response to input stimuli. In another highly cited paper, published in *Nature*, researchers from China and the USA collaborated to fabricate vertical OECTs by synthesizing new electro-active and ion-permeable semiconducting polymers and by the interface engineering of electro-active blend layers. This structure exhibits unprecedented performances in both p- and n-type operation modes.


2024 RESEARCH FRONTS

08

PHYSICS

2024 RESEARCH FRONTS

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN PHYSICS

The Top 10 Research Fronts in physics mainly focus on the subfields of condensed matter physics, theoretical physics, semiconductor physics, quantum physics, and high-energy physics. Three Research Fronts concentrate on condensed matter physics. Research on novel superconducting materials continues to be highly active, while hydrogen-rich compounds have now ranked among the hot Research Fronts for four consecutive years. Additionally, Kagome superconductors AV_3Sb_5 and infinite layer nickelates have also been recognized as hot Research Fronts for two consecutive years.

In theoretical physics, the modified theory of gravity known as f (Q) gravity theory has attracted much attention. In semiconductor physics, quantum dot light-emitting diodes, micro light-emitting diodes (micro-LEDs), and gallium oxide power devices emerge as hot topics. In quantum physics, twin-field quantum key distribution has registered as a hot topic for two consecutive years, while semiconductor quantum computing has newly emerged. In high-energy physics, the detection of the axion, one of the candidate particles proposed as a component of dark matter, has become a new hot topic.

Table 35: Top10 Research Fronts in physics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	High-temperature superconductivity in hydrogen-rich compounds under high pressure	30	4046	2021.5
2	Kagome superconductors AV_3Sb_5	45	5694	2021.1
3	f(Q) theory of gravity and its applications	26	2320	2021.1
4	Quantum dot light-emitting diodes	24	4059	2020.8
5	Superconductivity of infinite layer nickelates	25	2820	2020.7
6	Twin-field quantum key distribution	36	5682	2020.6
7	Semiconductor quantum computing	23	3736	2020.2
8	Axion dark matter search	17	2630	2020.2
9	The effect of size on micro-LEDs	15	2360	2020.1
10	Ga_2O_3 power devices	44	7990	2020.0

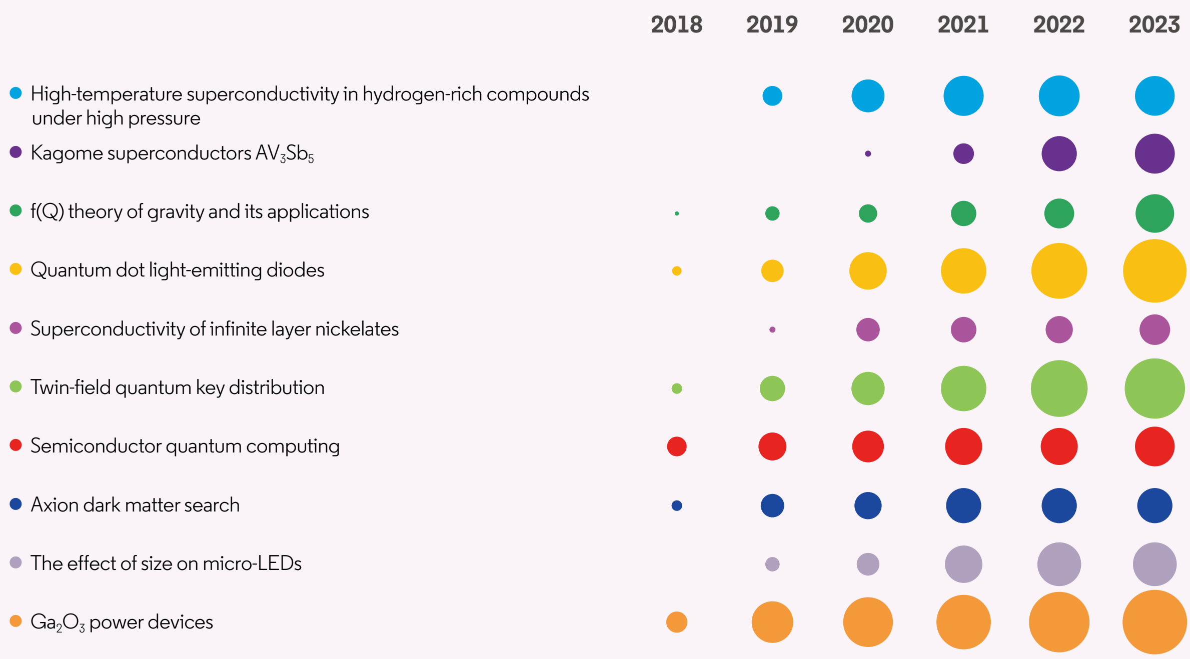


Figure 19: Citing papers for the Top 10 Research Fronts in physics

1.2 KEY HOT RESEARCH FRONT – "Semiconductor quantum computing"

Quantum computing (QC) has an exponential potential advantage compared with classical computing. Major countries around the world are vigorously promoting the development of QC. Several implementation approaches have been pursued for QC systems with great progress. Semiconductor QC is one of the important approaches that is compatible with the processes of modern semiconductor technology. The specialty area has received widespread attention from universities, research institutions, and large enterprises worldwide.

Silicon spin qubit research is the hot topic in semiconductor quantum computing, mainly focusing on the operation fidelity and integration of qubits. In recent years, significant breakthroughs have been made in the research of silicon spin qubits. In operation fidelity, this work has achieved single-qubit gate fidelities exceeding the fault tolerance threshold (over 99.9%), two-qubit gate fidelities over 99%, and germanium hole qubits and their ultrafast control. In integration of qubits, researchers have achieved advances in the strong coupling between spin qubits and superconducting cavities, four-qubit processors, six-qubit processors, and spin qubits control above one kelvin. The future of semiconductor QC remains wide open, and its ongoing development will provide a key step towards general-purpose quantum computers.

As for the citation frequency of individual core papers (Figure 20): The report on the discovery of single-qubit gate fidelities over 99.9% superconductivity, published in 2018 by researchers at RIKEN in Japan, has garnered the highest citation total, currently exceeding 470. Three papers have also attracted high rates of citation; these papers reported the demonstration of a programmable two-qubit quantum processor in a silicon by researchers at Delft University of Technology in the Netherlands in 2018 (439 citations); the realization of a quantum CNOT gate by researchers at Princeton University in the USA in 2018 (350 citations); and the strong coupling between spin qubits and superconducting cavities by Princeton researchers in 2018 (250 citations). In addition, publications on the strong coupling between spin qubits and superconducting cavities reported by Delft University in 2019, on spin qubits control above one kelvin achieved by the University of New South Wales in Australia in 2020, and on the demonstration of a four-qubit germanium quantum processor by Delft University in 2021, have also been widely cited.

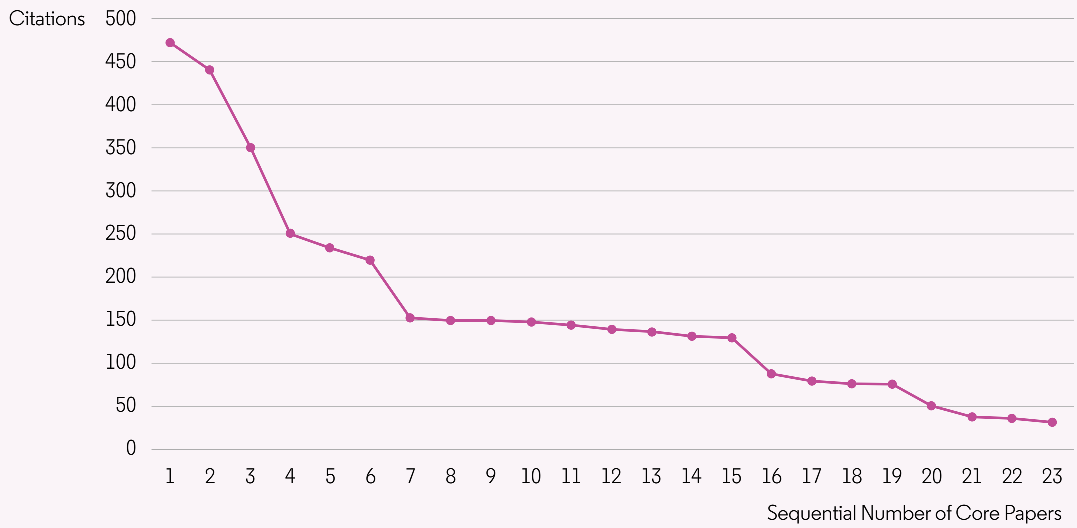


Figure 20: Citation frequency distribution curve of core papers in the Research Front "Semiconductor quantum computing"

The Netherlands and the USA are the most active countries in this front. Authors based in the two nations participated in 12 and 11 core papers, respectively (Table 36), accounting for 52.2% and 47.8% of the total. Japan and Australia also demonstrate strong performance. Among individual organizations, Delft University of Technology contributed the highest numbers of core papers, followed by Netherlands Organisation for Applied Scientific Research and Princeton University. On the list of top institutions, five are based in the USA, while Japan is host to three, the Netherlands and Canada contain two each, and Australia, China, and Germany each claim one.

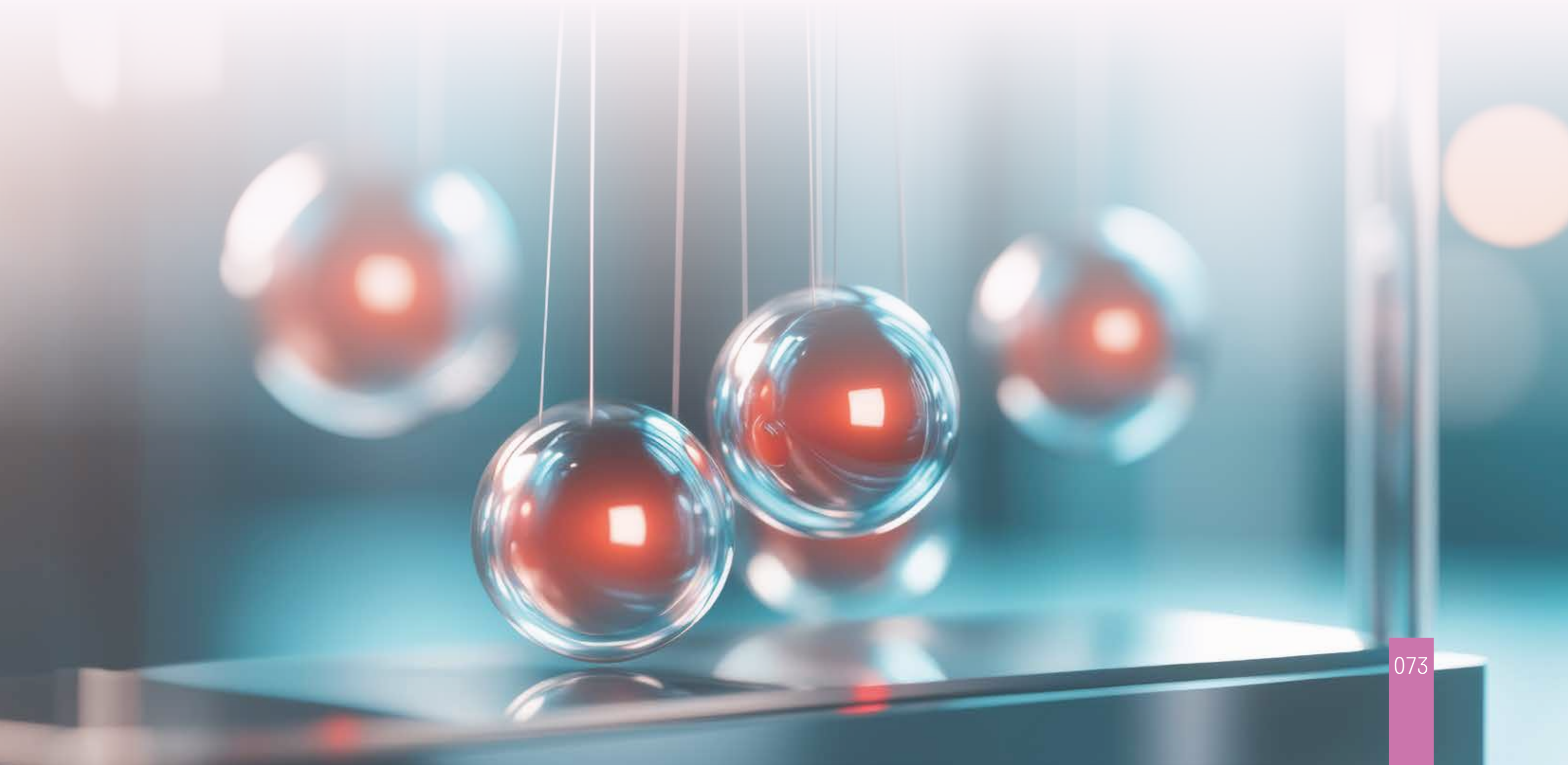
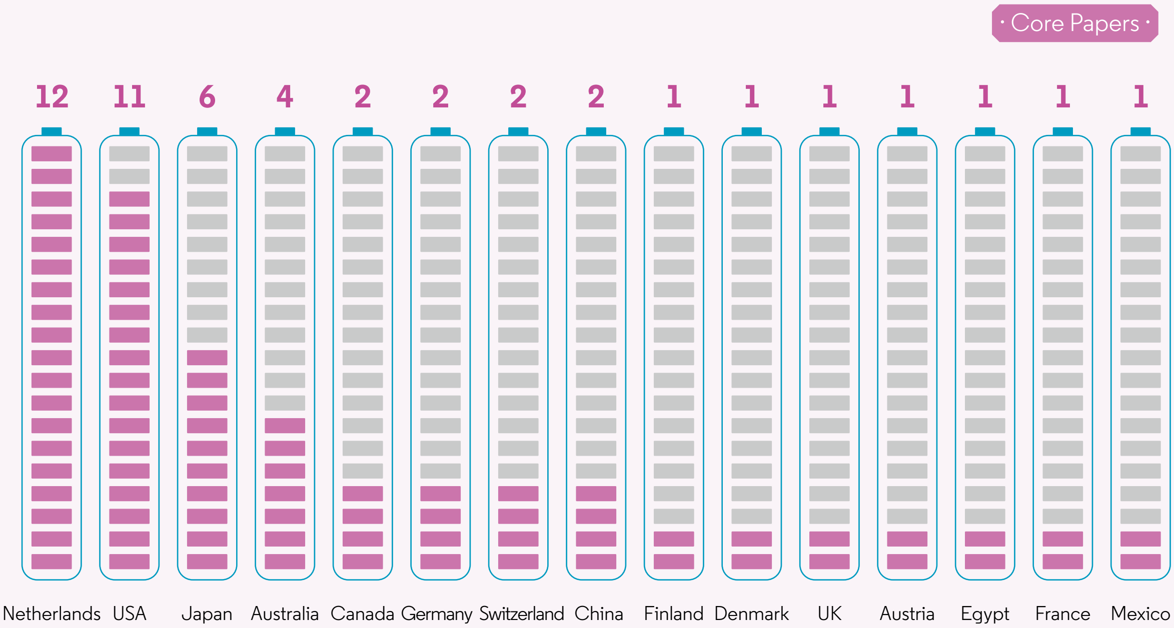


Table 36: Top countries and institutions producing core papers in the Research Front "Semiconductor quantum computing"

Country Ranking	Country	Core Papers	Proportion
1	Netherlands	12	52.2%
2	USA	11	47.8%
3	Japan	6	26.1%
4	Australia	4	17.4%
5	Canada	2	8.7%
5	Germany	2	8.7%
5	Switzerland	2	8.7%
5	China	2	8.7%
9	Finland	1	4.3%
9	Denmark	1	4.3%
9	UK	1	4.3%
9	Austria	1	4.3%
9	Egypt	1	4.3%
9	France	1	4.3%
9	Mexico	1	4.3%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Delft University of Technology	Netherlands	12	52.2%
2	Netherlands Organisation for Applied Scientific Research	Netherlands	8	34.8%
3	Princeton University	USA	5	21.7%
4	University of New South Wales	Australia	4	17.4%
4	Keio University	Japan	4	17.4%
6	National Institute of Standards and Technology	USA	3	13.0%
6	Intel Corporation	USA	3	13.0%
8	Canadian Institute for Advanced Research	Canada	2	8.7%
8	University of Tokyo	Japan	2	8.7%
8	Chinese Academy of Sciences	China	2	8.7%
8	Riken	Japan	2	8.7%
8	University of Sherbrooke	Canada	2	8.7%
8	Sandia National Laboratory	USA	2	8.7%
8	University of Konstanz	Germany	2	8.7%
8	University of Maryland College Park	USA	2	8.7%



In terms of papers that cite the core literature (Table 37), the USA is the most prolific country, with citing-paper counts far exceeding those of other nations. China, Germany, Japan, Australia, and the Netherlands rank 2nd to 5th. Among the top institutions, the Chinese Academy of Sciences published the most citing papers, followed by University of New South Wales and Delft University of Technology. On the list of citing institutions, France is host to four, while China contains two, and Australia, the Netherlands, Switzerland, and Germany are each home to one.

Table 37: Top countries and institutions producing citing papers in the Research Front "Semiconductor quantum computing"

Country Ranking	Country	Citing Papers	Proportion
1	USA	432	30.9%
2	China	268	19.2%
3	Germany	189	13.5%
4	Japan	166	11.9%
5	Australia	147	10.5%
6	Netherlands	132	9.4%
7	UK	113	8.1%
8	France	112	8.0%
8	Switzerland	112	8.0%
10	Canada	91	6.5%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Chinese Academy of Sciences	China	119	8.5%
2	University of New South Wales	Australia	114	8.2%
3	Delft University of Technology	Netherlands	112	8.0%
4	French Alternative Energies and Atomic Energy Commission (CEA)	France	67	4.8%
5	Communaute Universite Grenoble Alpes	France	66	4.7%
5	University of Science and Technology of China	China	66	4.7%
7	University of Grenoble Alps	France	65	4.7%
8	United States Department of Energy (DOE)	USA	63	4.5%
9	National Center for Scientific Research of France (CNRS)	France	54	3.9%
10	University of Basel	Switzerland	52	3.7%

1.3 KEY HOT RESARCH FRONT– "Axion dark matter search"

Dark matter is one of the biggest unsolved mysteries in modern physics and cosmology. Weakly interacting massive particles (WIMPs) have been the leading candidate for dark matter for many years, and multiple international dark matter experiments are targeting WIMPs. In recent years, axions – another candidate for dark matter – have attracted widespread attention. Many countries have developed experimental approaches to this question, such as the Axion Dark Matter eXperiment (ADMX) and HAYSTAC experiment in the USA, CULTASK in South Korea, and MADMAX in Germany. These experiments have made great progress, launching the axion dark matter search to prominence as a hot topic.

As for the citation frequency of individual core papers (Figure 21), a review article on the new experimental approaches in the search for axion-like particles, published by researchers at Universidad de Zaragoza in Spain in 2018, has garnered the highest citation count, now surpassing 440. Subsequently, a paper that reported the results excluding the range of dark matter axions with masses between 2.66 and 2.81 μeV, published by the ADMX Collaboration in 2018, and a 2020 review on QCD axion models reported by National Institute of Nuclear Physics (INFN) in Italy, have respectively earned citation counts of 320 and 314 at this writing. In addition, the experimental results excluding the range of dark matter axions with masses between 2.81 and 3.31 μeV, reported by the ADMX collaboration in 2020, along with work excluding the range of 23.15 and 24.0 μeV (2018), 16.96 and 17.12 μeV, and 17.14 and 17.28 μeV (2021) through the HAYSTAC experiment reported by Yale University, as well as the first experimental result of the ABRACADABRA experiment published by the MIT in 2019, have also achieved high citations.

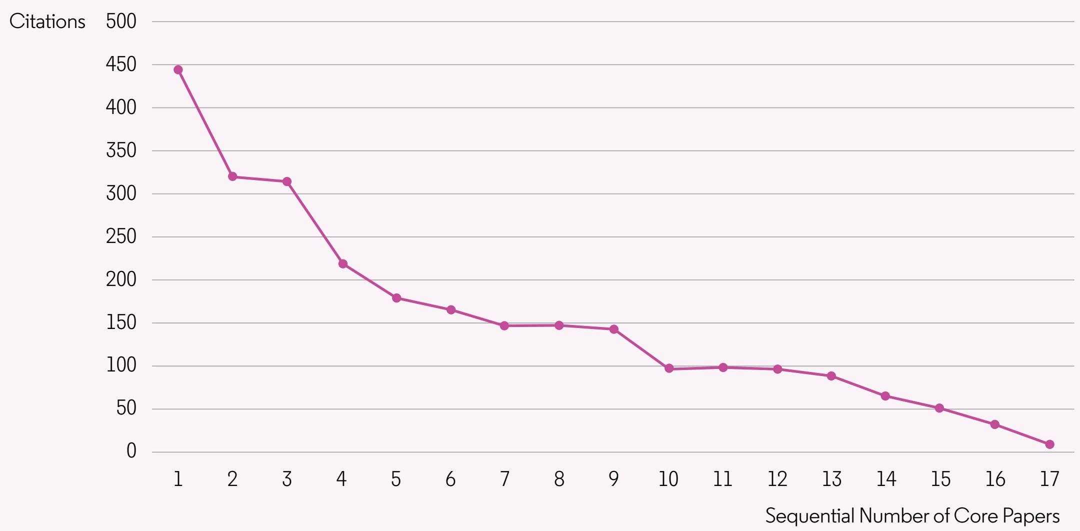


Figure 21: Citation frequency distribution curve of core papers in the Research Front "Axion dark matter search"

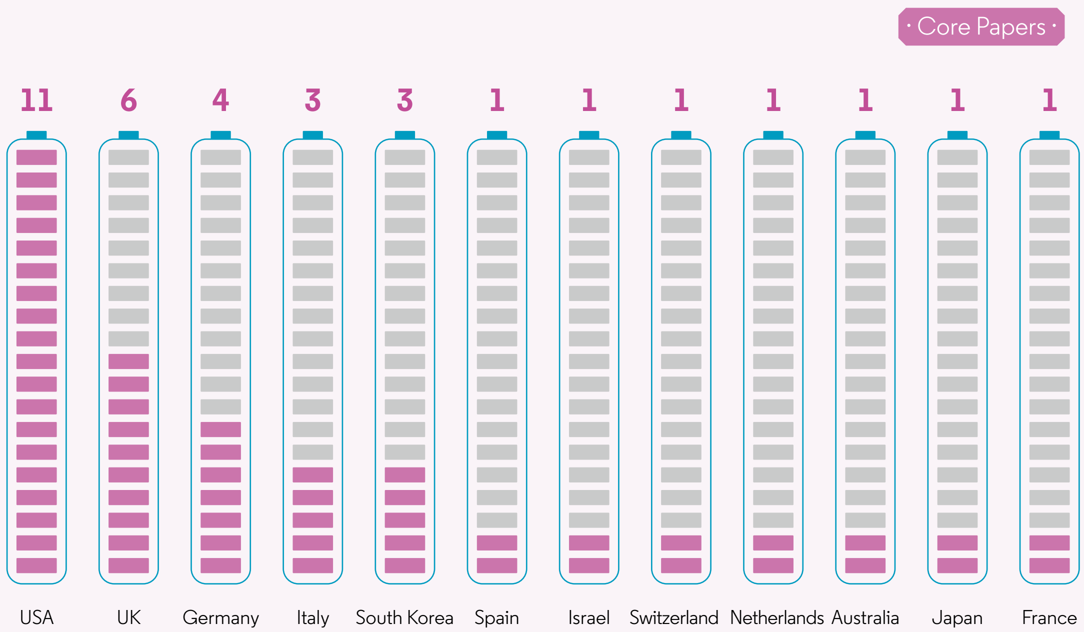
The USA is the most active country in this front, participating in 11 core papers, and accounting for 64.7% of the total (Table 38). The UK, Germany, Italy, and South Korea also demonstrate notable performance. The top six institutions are all based in the USA, with the University of California Berkeley, the University of Chicago, and Lawrence Livermore National Laboratory ranking 1st to 3rd.

Among the top institutions, the USA contains nine, while South Korea claims three, and the UK is home to one.

Table 38: Top countries and institutions producing core papers in the Research Front "Axion dark matter search"

Country Ranking	Country	Core Papers	Proportion
1	USA	11	64.7%
2	UK	6	35.3%
3	Germany	4	23.5%
4	Italy	3	17.6%
4	South Korea	3	17.6%
6	Spain	1	5.9%
6	Israel	1	5.9%
6	Switzerland	1	5.9%
6	Netherlands	1	5.9%
6	Australia	1	5.9%
6	Japan	1	5.9%
6	France	1	5.9%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of California Berkeley	USA	7	41.2%
2	University of Chicago	USA	5	29.4%
2	Lawrence Livermore National Laboratory	USA	5	29.4%
4	National Institute of Standards and Technology	USA	4	23.5%
4	University of Florida	USA	4	23.5%
4	Fermi National Accelerator Laboratory in Illinois	USA	4	23.5%
7	Korea Advanced Institute of Science & Technology (KAIST)	South Korea	3	17.6%
7	Pacific Northwest National Laboratory	USA	3	17.6%
7	University of Michigan	USA	3	17.6%
7	Korea Aerospace Research Institute	South Korea	3	17.6%
7	Institute for Basic Science	South Korea	3	17.6%
7	University of Washington	USA	3	17.6%
7	University of Sheffield	UK	3	17.6%

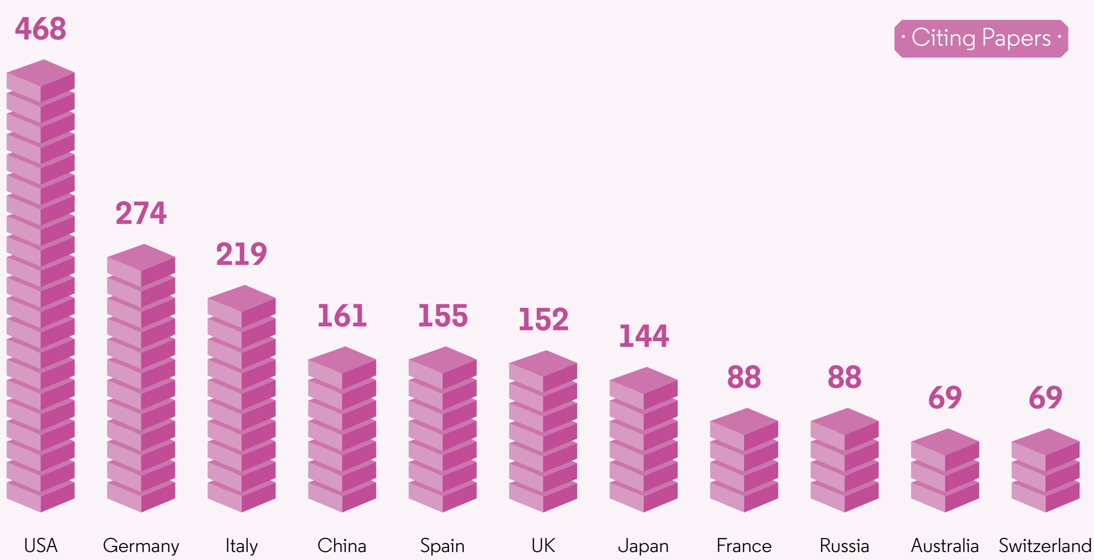


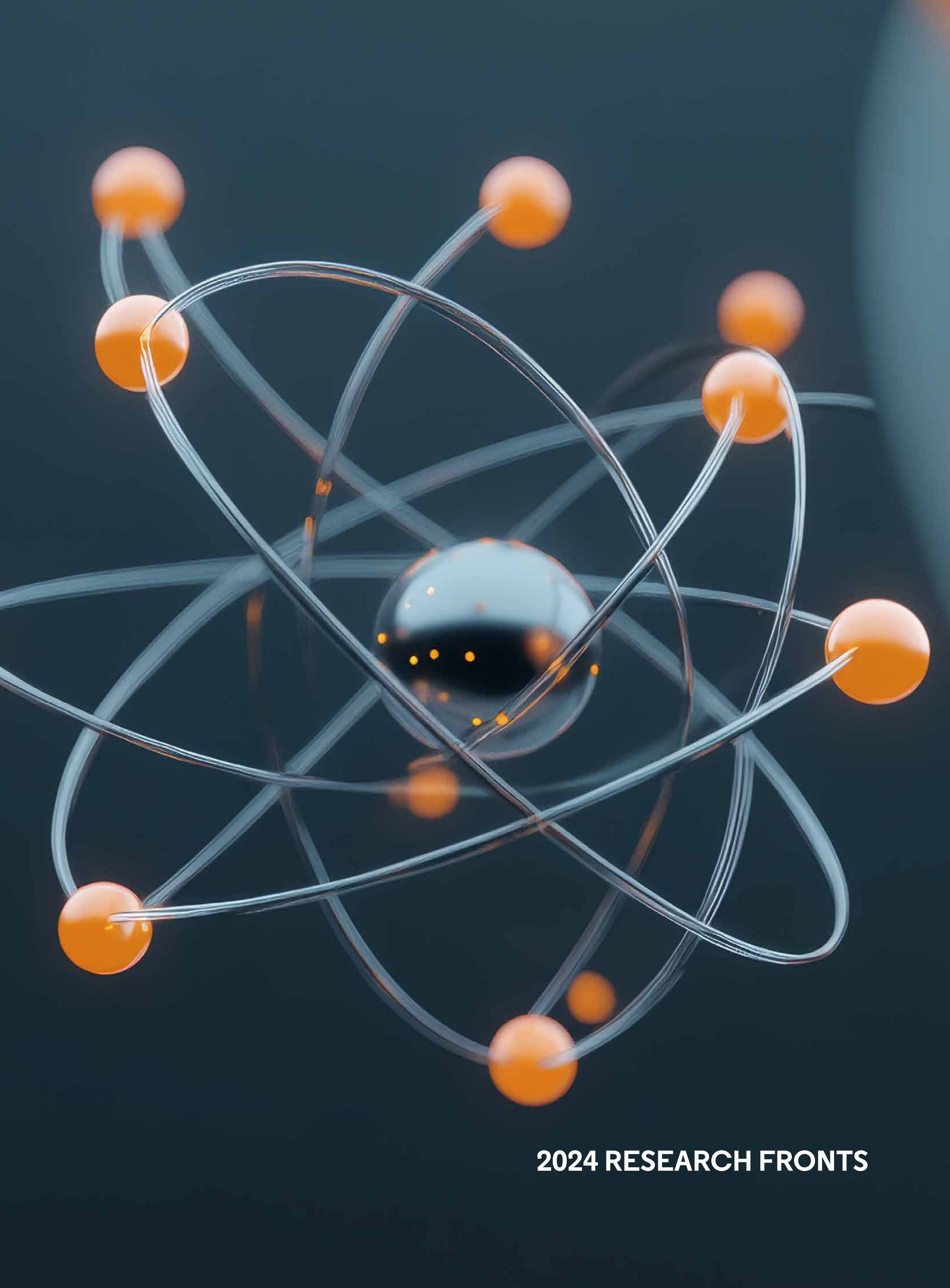
Analysis of the citing papers (Table 39) indicates that the USA remains the most active in this front, with citing-paper counts far above those of other countries. Germany, Italy, and China also perform well. The INFN published the most numerous citing papers, followed by Helmholtz Association, Spanish National Research Council (CSIC) and the University of California Berkeley. Among the top citing institutions, the USA is host to three, while Germany contains two, and Italy, Spain, Japan, France, and China each claim one.

Table 39: Top countries and institutions producing citing papers in the Research Front "Axion dark matter search"

Country Ranking	Country	Citing Papers	Proportion
1	USA	468	38.3%
2	Germany	274	22.4%
3	Italy	219	17.9%
4	China	161	13.2%
5	Spain	155	12.7%
6	UK	152	12.4%
7	Japan	144	11.8%
8	France	88	7.2%
8	Russia	88	7.2%
10	Australia	69	5.7%
10	Switzerland	69	5.7%

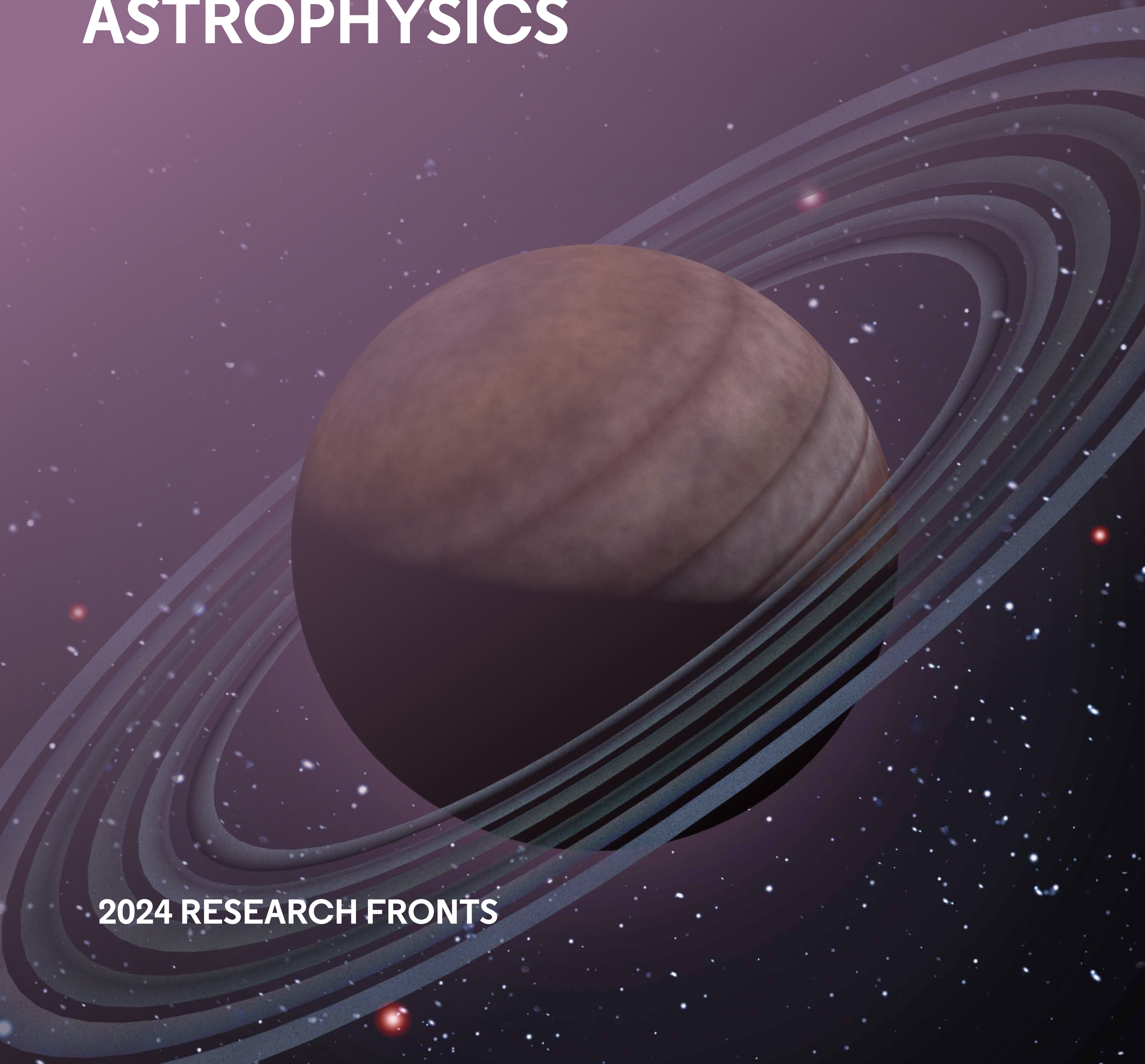
Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	National Institute of Nuclear Physics (INFN)	Italy	183	15.0%
2	Helmholtz Association	Germany	102	8.4%
3	Spanish National Research Council (CSIC)	Spain	98	8.0%
4	University of California Berkeley	USA	88	7.2%
5	University of Tokyo	Japan	81	6.6%
6	University of Chicago	USA	75	6.1%
7	National Center for Scientific Research of France (CNRS)	France	74	6.1%
8	Max Planck Society	Germany	73	6.0%
9	Stanford University	USA	67	5.5%
10	Chinese Academy of Sciences	China	65	5.3%




2024 RESEARCH FRONTS

09

ASTRONOMY AND ASTROPHYSICS



1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN ASTRONOMY AND ASTROPHYSICS

The Top 10 Research Fronts in astronomy and astrophysics cover a wide range of topics, including gravitational waves, cosmology, black holes, dark matter and dark energy, and galactic surveys. Notably, work on the theoretical analysis and detection of gravitational waves has shown remarkable progress. Several hot Research Fronts pertain to this research, including "Nanohertz gravitational waves detected by pulsar timing arrays", "Binary black hole merger event GW190521", "Gravitational waves from binary black hole mergers and properties of black holes", "Properties of compact objects from the LIGO-Virgo Gravitational-Wave Transient Catalog", and "Black hole shadows and the 4D Einstein-Gauss-Bonnet theory of gravity".

In terms of cosmological research, the "Hubble constant tension and cosmology" has become a hot Research Front for the first time, while the cosmological implications of the string theory swampland have once again made it to the list. Black holes, along with dark matter and dark energy, continue to receive considerable attention, with relevant Research Fronts including the observation of M87 black hole by the Event Horizon Telescope and the investigation of dark matter and dark energy through cosmic shear surveys. In addition, a data release from the Gaia space observatory has once again made the list.

Table 40: Top 10 Research Fronts in astronomy and astrophysics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Hubble constant tension and cosmology	10	2120	2021.7
2	Gaia Early Data Release 3	6	2869	2021.0
3	Nanohertz gravitational waves detected by pulsar timing arrays	6	1117	2021.0
4	M87 black hole observation by the Event Horizon Telescope	2	368	2021.0
5	Binary black hole merger event GW190521	5	1037	2020.6
6	Dark matter and dark energy research by cosmic shear surveys	13	2961	2020.2
7	Gravitational waves from binary black hole mergers and properties of black holes	27	3238	2020.1
8	Properties of compact objects from LIGO-Virgo Gravitational-Wave Transient Catalog	4	3358	2020.0
9	Black hole shadows and the 4D Einstein-Gauss-Bonnet theory of gravity	19	2674	2020.0
10	Cosmological implications of the string theory swampland	15	3047	2019.5

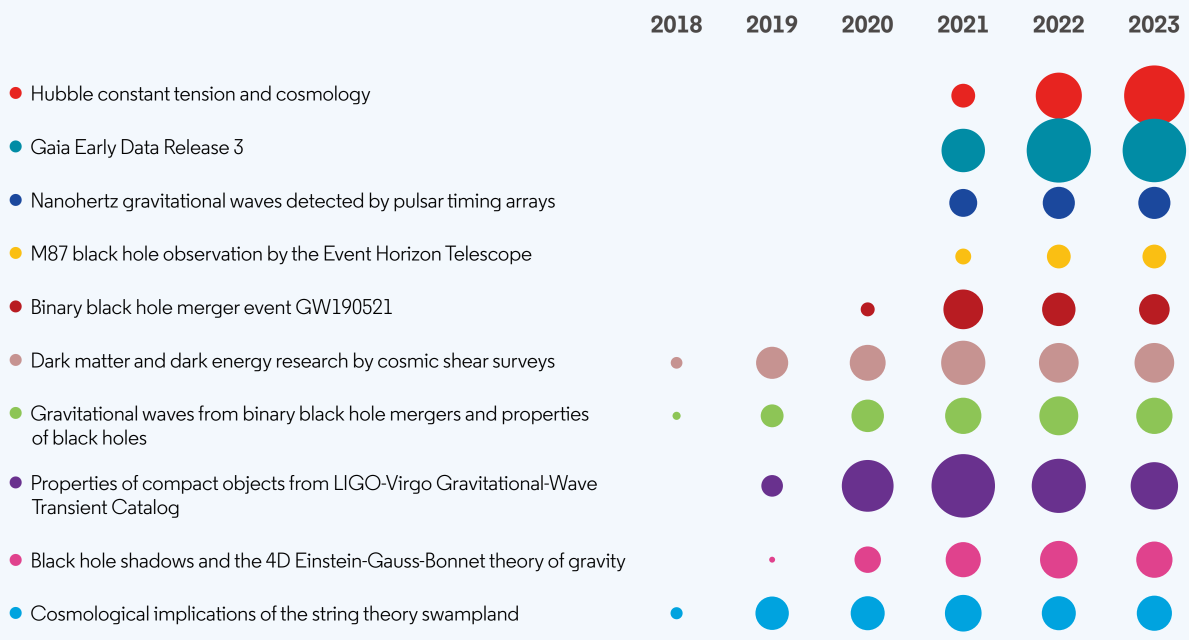


Figure 22: Citing papers for the Top 10 Research Fronts in astronomy and astrophysics

1.2 KEY HOT RESEARCH FRONT – "Hubble constant tension and cosmology"

In 1929, American astronomer Edwin Hubble discovered that galaxies farther from Earth were receding at higher speeds, indicating that the universe is expanding at an accelerating rate. Hubble developed a method for calculating the distances to celestial objects using a type of star with periodic brightness variations – Cepheid variable stars – as "standard candles". He derived the ratio of the increase in the velocity of receding galaxies to their distance as 500 $km\ s^{-1}\ Mpc^{-1}$, a value later known as the Hubble constant.

In the 1980s, Hubble's academic successor Allan Sandage utilized more powerful astronomical telescopes and found that Hubble's original calculations were overestimated. He adjusted the Hubble constant to approximately 50 $km\ s^{-1}\ Mpc^{-1}$.

Since 2015, a significant debate has arisen in astronomy and physics regarding the discrepancy between the Hubble constant derived from the cosmic microwave background (CMB) and the value calculated using traditional astronomical methods. The CMB represents the "afterglow" of the Big Bang, and the universe's expansion rate can be determined by measuring the anisotropies in the temperature and polarization of the CMB in conjunction with the Lambda cold dark matter (ΛCDM) cosmological model. The Hubble constant derived from data from the European Space Agency's Planck mission is $67.27 \pm 0.60\ km\ s^{-1}\ Mpc^{-1}$.

In 2022, a team led by Nobel Prize-winning physicist Adam Riess of Johns Hopkins University in the USA, using observational data from Cepheid variable stars and supernovae, calculated the Hubble constant to be approximately $73.04 \pm 1.04\ km\ s^{-1}\ Mpc^{-1}$.

The Hubble constant derived from the "standard candle" method is larger than the values obtained from measurements of the cosmic microwave background radiation. Most scientists agree that this discrepancy cannot be attributed to statistical errors, leading to a conundrum known as the "Hubble constant tension". If both calculations are validated by independent methods, it would require a re-evaluation of cosmological laws and provide insights into new physics beyond general relativity and quantum mechanics.

The Hot Research Front "Hubble constant tension and cosmology" features 10 core papers that highlight recent advances by various research teams in measuring the Hubble constant through different methods, as well as proposed solutions to Hubble constant tension. One of the most-cited papers comes from the international led collaboration "Supernova H0 for the Equation of State" (SH0ES), by Adam Riess. In 2022, the team made significant updates to the Hubble constant based on nearly 30 years of observations from the Hubble Space Telescope (HST), achieving a measurement uncertainty of just 1%, with an error probability of only one in a million. Other core papers include measurements of the Hubble constant using CMB power spectrum data, baryon acoustic oscillations, and Pantheon+ supernova data, among other methods.

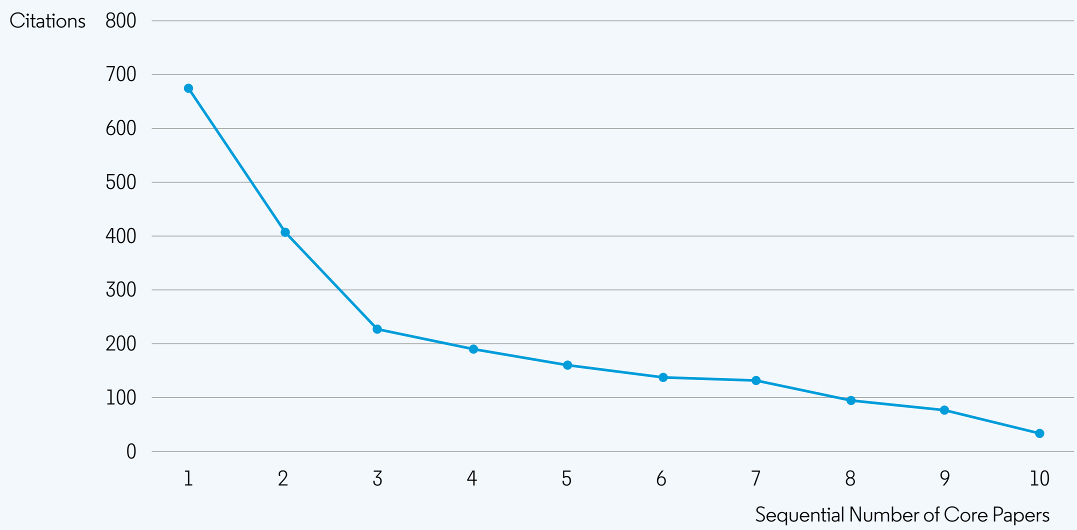


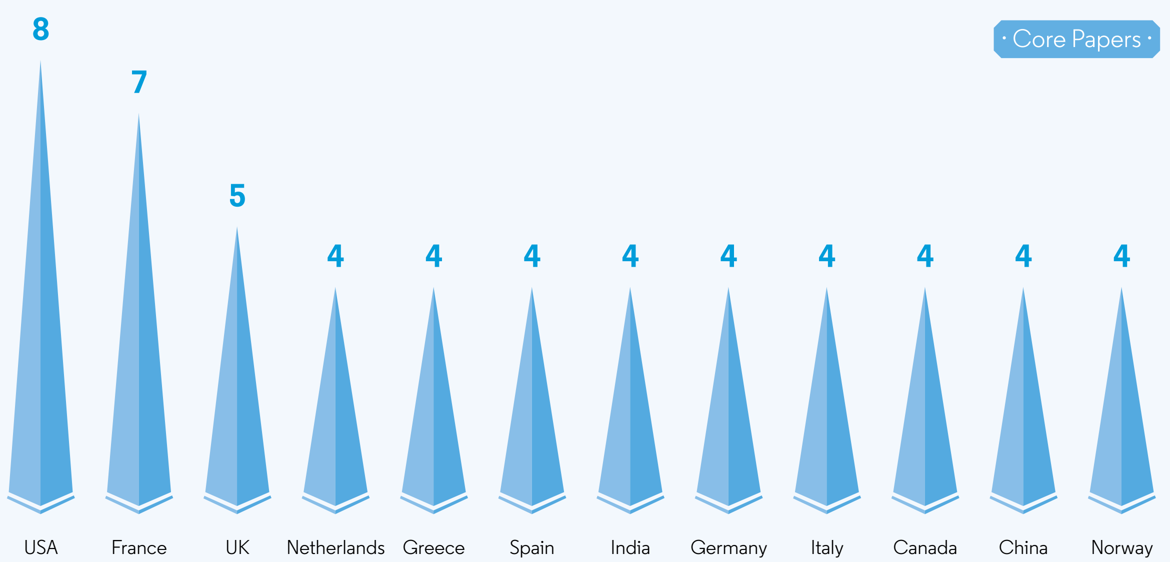
Figure 23: Citation frequency distribution curve of core papers in the Research Front "Hubble constant tension and cosmology"

According to the analysis of core papers by country and institution, the USA has excelled in this front, having led or participated in most of the research, contributing eight core papers. France and the UK rank 2nd and 3rd, with seven and five core papers, respectively. As the initiating institution of the SH0ES international scientific collaboration program, Johns Hopkins University has undoubtedly contributed the most core papers. French institutions such as the National Center for Scientific Research (CNRS) and the Sorbonne University have also performed exceptionally well. Many of the core papers resulted from collaborations among various research institutions worldwide, highlighting the crucial role of international cooperation in advancing research in this field.

Table 41: Top countries and institutions producing core papers in the Research Front "Hubble constant tension and cosmology"

Country Ranking	Country	Core Papers	Proportion
1	USA	8	80.0%
2	France	7	70.0%
3	UK	5	50.0%
4	Netherlands	4	40.0%
4	Greece	4	40.0%
4	Spain	4	40.0%
4	India	4	40.0%
4	Germany	4	40.0%
4	Italy	4	40.0%
4	Canada	4	40.0%
4	China	4	40.0%
4	Norway	4	40.0%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Johns Hopkins University	USA	7	70.0%
1	National Center for Scientific Research (CNRS) of France	France	7	70.0%
3	Sorbonne University	France	5	50.0%

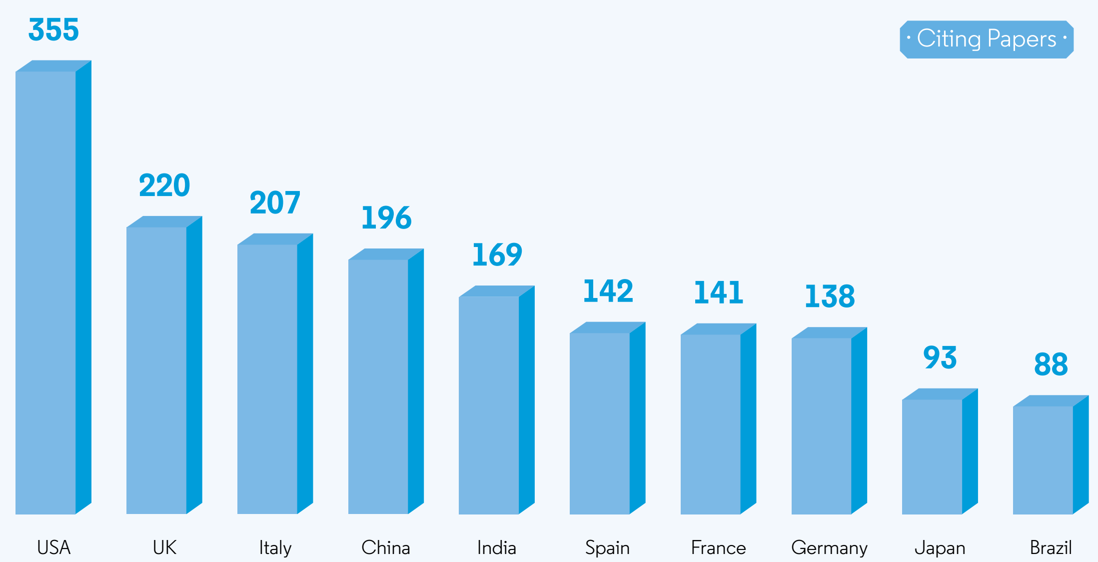


As for citing papers, the USA ranks 1st, accounting for 29.0% of the citing reports, while China ranks 4th, showing strong growth in this front. The Italian National Institute of Nuclear Physics (INFN) ranks 1st among the top 10 citing institutions, followed by France's CNRS and the Chinese Academy of Sciences. The USA-based entities occupy three positions among the Top 10 citing institutions, with the United States Department of Energy (DOE) ranking 6th and Johns Hopkins University and the University of Chicago tied for 7th.

Table 42: Top countries and institutions producing citing papers in the Research Front "Hubble constant tension and cosmology"

Country Ranking	Country	Citing Papers	Proportion
1	USA	355	29.0%
2	UK	220	18.0%
3	Italy	207	16.9%
4	China	196	16.0%
5	India	169	13.8%
6	Spain	142	11.6%
7	France	141	11.5%
8	Germany	138	11.3%
9	Japan	93	7.6%
10	Brazil	88	7.2%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	National Institute of Nuclear Physics (INFN)	Italy	132	10.8%
2	National Center for Scientific Research of France (CNRS)	France	128	10.5%
3	Chinese Academy of Sciences	China	92	7.5%
4	National Institute for Astrophysics (INAF)	Italy	79	6.5%
5	Spanish National Research Council (CSIC)	Spain	76	6.2%
6	United States Department of Energy (DOE)	USA	57	4.7%
7	Johns Hopkins University	USA	55	4.5%
7	Max Planck Society	Germany	55	4.5%
7	University of Chicago	USA	55	4.5%
10	University of Cambridge	UK	54	4.4%



1.3 KEY HOT RESEARCH FRONT – "Nanohertz gravitational waves detected by pulsar timing arrays"

Pulsars are rapidly spinning neutron stars that emit radio-frequency beams from their magnetic poles. As the beams sweep across the Earth, radio telescopes detect regular signals with precision comparable to atomic clocks. This regularity is key to gravitational-wave detection. If a gravitational wave passes between a pulsar and the Earth, the resulting space-time distortion would slightly alter the detected tick rate, causing it to speed up or slow down.

However, the signal from a pulsar can also be influenced by pulsar fluctuations or by interactions between the beam and the interstellar medium. To ensure reliable observations, astronomers combine signals from tens of pulsars in the Milky Way, forming a pulsar timing array (PTA).

In 2023, several PTA collaborations reported evidence for a stochastic background of nanohertz gravitational waves, using radio telescopes across North America, Europe, India, China, and Australia. Among them, the Chinese Pulsar Timing Array (CPTA) collaboration used the Five-hundred-meter Aperture Spherical Radio Telescope (FAST). The detection of low-frequency background gravitational waves has opened a new observational window for studying their astrophysical and cosmological origins. Researchers concur that a natural explanation involves pairs of supermassive black holes (SMBHs). When two galaxies merge, the SMBHs at their centers can form a binary pair, orbiting each other for thousands or millions of years before eventually merging. The movement of these supermassive bodies generates gravitational waves at nanohertz frequencies. Additional source candidates also include inflationary processes in the early Universe, such as inflation, and potential new physics related to dark matter.

The hot Research Front "Nanohertz gravitational waves detected by pulsar timing arrays" includes six core papers published between 2020 and 2022. These papers delve into the search for evidence of a stochastic background of nanohertz gravitational waves by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), the Parkes PTA(PPTA) in Australia, and the European Pulsar Timing Array (EPTA). Additionally, the reports explore the role of cosmic strings as one possible cosmological process responsible for generating a stochastic background of nanohertz gravitational waves. The most-cited paper in this Research Front analyzes the 12.5-year pulsar-timing dataset collected by NANOGrav, uncovering strong evidence for a stochastic gravitational wave background.

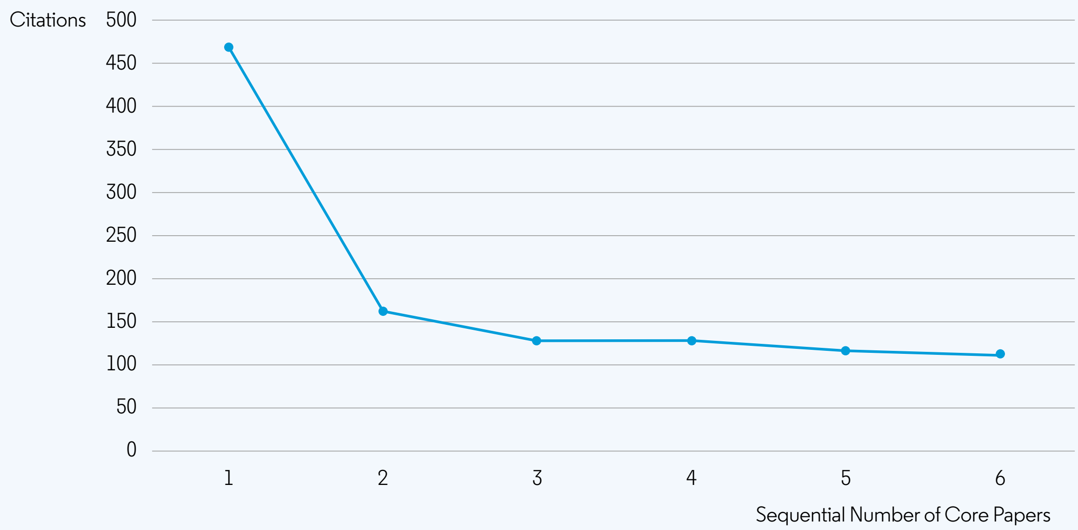


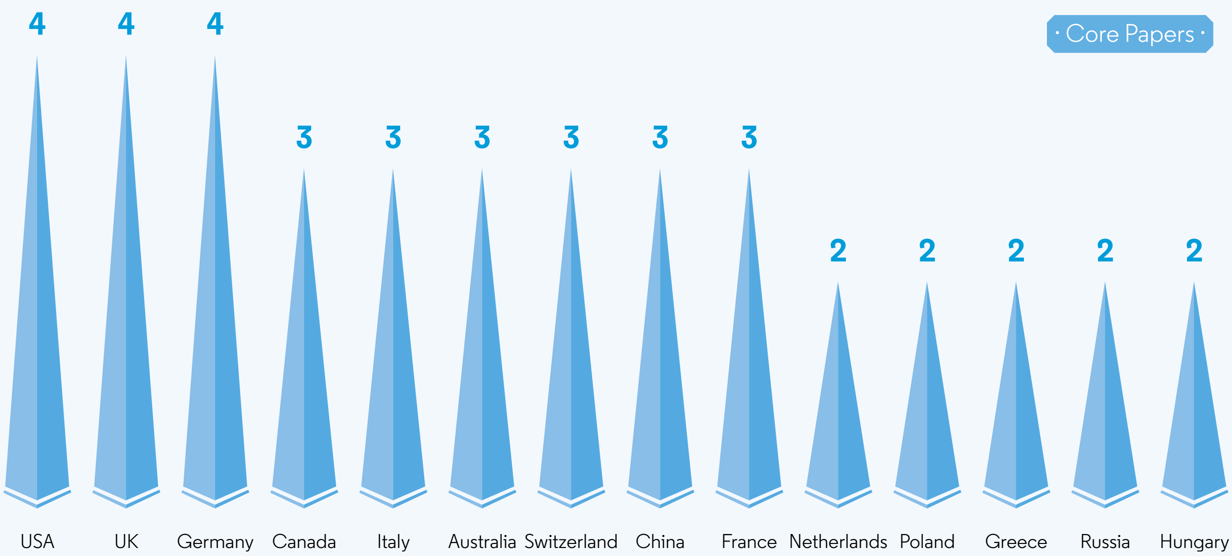
Figure 24: Citation frequency distribution curve of core papers in the Research Front "Nanohertz gravitational waves detected by pulsar timing arrays"

Regarding the core-paper contributions by country, the USA, the UK, and Germany each contributed four papers, while Canada, Italy, Australia, Switzerland, China, and France each contributed three. As for contributions by institutions, the German Max Planck Society led with four core papers. Six French institutions, including the CNRS, the Paris Observatory, and the University of Orléans, each contributed three core papers, as did NASA, the US Department of Defense, the University of Manchester in the UK, the Chinese Academy of Sciences, CERN, the University of Toronto in Canada, and Swinburn University of Technology in Australia.

Table 43: Top countries and institutions producing core papers in the Research Front "Nanohertz gravitational waves detected by pulsar timing arrays"

Country Ranking	Country	Core Papers	Proportion
1	USA	4	66.7%
1	UK	4	66.7%
1	Germany	4	66.7%
4	Canada	3	50.0%
4	Italy	3	50.0%
4	Australia	3	50.0%
4	Switzerland	3	50.0%
4	China	3	50.0%
4	France	3	50.0%
10	Netherlands	2	33.3%
10	Poland	2	33.3%
10	Greece	2	33.3%
10	Russia	2	33.3%
10	Hungary	2	33.3%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Max Planck Society	Germany	4	66.7%
2	University of Manchester	UK	3	50.0%
2	Chinese Academy of Sciences	China	3	50.0%
2	Observatoire de Paris	France	3	50.0%
2	European Organization for Nuclear Research (CERN)	Switzerland	3	50.0%
2	National Center for Scientific Research of France (CNRS)	France	3	50.0%
2	University of Orleans	France	3	50.0%
2	National Aeronautics & Space Administration (NASA)	USA	3	50.0%
2	University of Toronto	Canada	3	50.0%
2	Universite PSL	France	3	50.0%
2	Centre Val Loire ComUE	France	3	50.0%
2	University of Confederale Leonard de Vinci	France	3	50.0%
2	United States Department of Defense	USA	3	50.0%
2	Swinburne University of Technology	Australia	3	50.0%

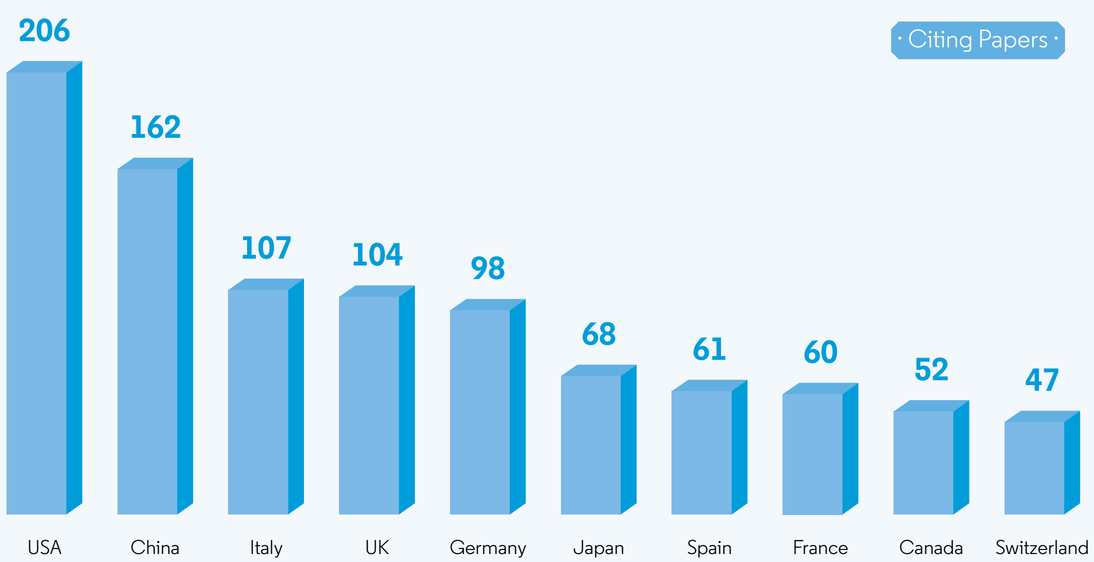


As for citing papers, the USA ranks 1st, followed by China, Italy, the UK, and Germany. In terms of the citing institutions, the Italian National Institute of Nuclear Physics ranks 1st, followed by the Chinese Academy of Sciences, the CNRS in France, the Max Planck Society in Germany, and NASA in the USA.

Table 44: Top countries and institutions producing citing papers in the Research Front "Nanohertz gravitational waves detected by pulsar timing arrays"

Country Ranking	Country	Citing Papers	Proportion
1	USA	206	36.1%
2	China	162	28.4%
3	Italy	107	18.7%
4	UK	104	18.2%
5	Germany	98	17.2%
6	Japan	68	11.9%
7	Spain	61	10.7%
8	France	60	10.5%
9	Canada	52	9.1%
10	Switzerland	47	8.2%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	National Institute of Nuclear Physics (INFN)	Italy	88	15.4%
2	Chinese Academy of Sciences	China	86	15.1%
3	National Center for Scientific Research of France (CNRS)	France	54	9.5%
4	Max Planck Society	Germany	53	9.3%
5	National Aeronautics & Space Administration (NASA)	USA	42	7.4%
6	Universite PSL	France	40	7.0%
7	California Institute of Technology	USA	39	6.8%
7	University of Tokyo	Japan	39	6.8%
9	Observatoire de Paris	France	37	6.5%
9	Peking University	China	37	6.5%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN ASTRONOMY AND ASTROPHYSICS

One emerging Research Fronts entitled "Preliminary results of JWST" has been identified in astronomy and astrophysics.

Table 45: Emerging Research Fronts in astronomy and astrophysics

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Preliminary results of JWST	48	2066	2022.9

2.2 KEY EMERGING RESEARCH FRONT – "Preliminary results of JWST"

The James Webb Space Telescope (JWST) is the successor to the Hubble Space Telescope, aiming to address unresolved questions about the Universe and drive groundbreaking discoveries across all areas of astronomy.

JWST is an orbiting infrared observatory with a wavelength range of 0.6 to 28.5 microns, designed to complement and expand on Hubble's achievements with extended wavelength coverage and significantly enhanced sensitivity. At 6.5 meters wide, JWST's primary mirror is the largest ever built for a space-based telescope. JWST has four mission objectives: to search for the first galaxies or luminous objects formed after the Big Bang; to study the evolution of galaxies from their origins to the present; to observe the process of star formation from the initial stages to the formation of planetary systems; and to measure the physical and chemical properties of planetary systems, including those in our own solar system, assessing their potential for life. The JWST is equipped with four cutting-edge instruments: the Near Infrared Camera (NIRCam), the Near Infrared Spectrograph (NIRSpec), the Mid Infrared Instrument (MIRI), and the Fine Guidance Sensors/Near Infrared Imager and Slitless Spectrograph (FGS/NIRISS).

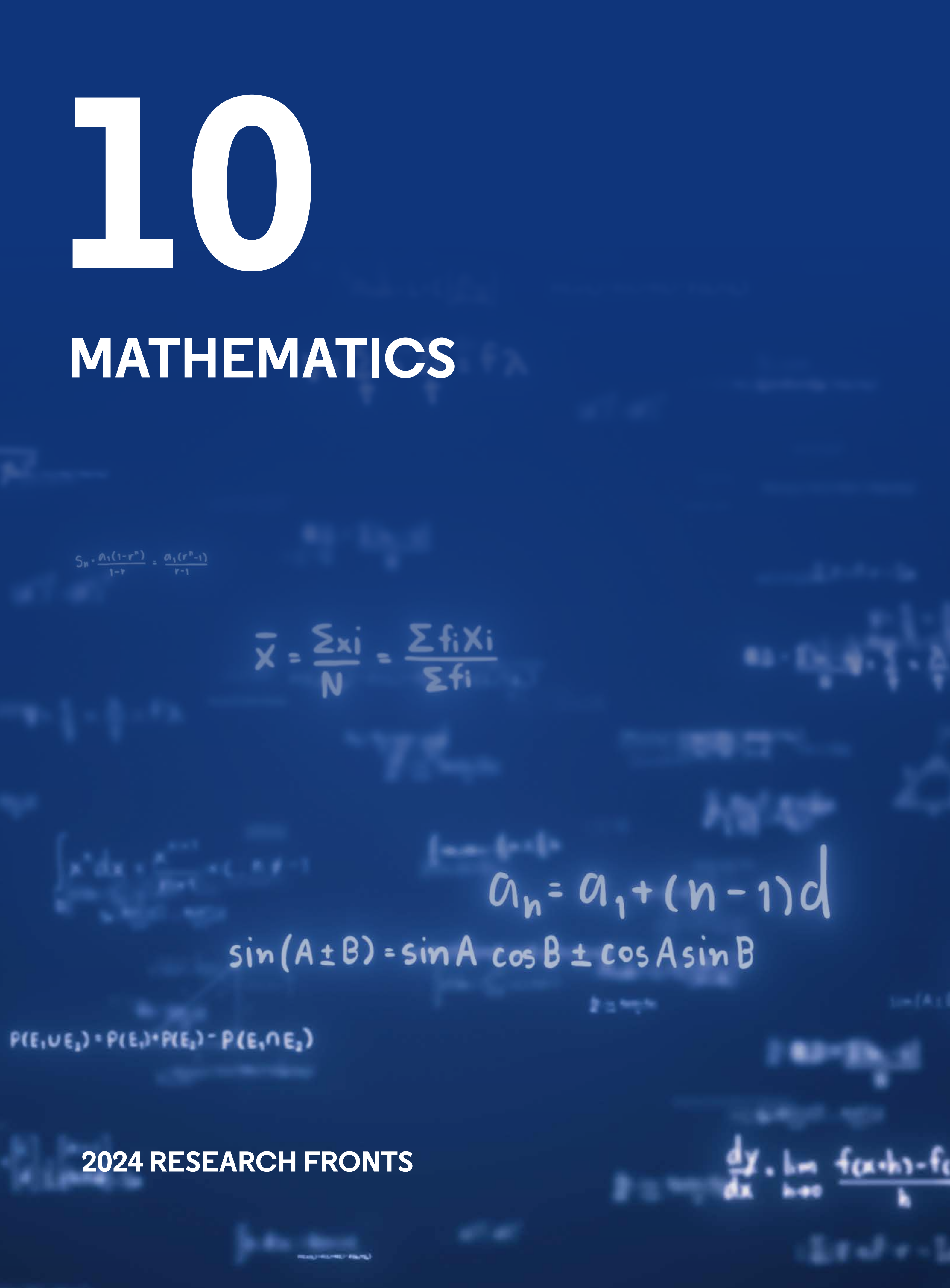
JWST is an international collaboration that includes NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). Thousands of scientists, engineers and technicians from 14 countries were involved in the JWST's design, construction, test, integration, launch, commissioning, and operations. In July 2022, JWST released its first full-color images and spectroscopic data, marking the official start of its general science operations.

This emerging Research Front brings together 48 core papers published between 2022 and 2023, showcasing the major scientific discoveries made since the launch of JWST. Research topics include the early release of observational images and spectral datasets, and survey plans based on early observational data, as well as observational discoveries about the reionization period of the Universe, high-redshift galaxies, and more.

According to the mission plan, JWST will operate for five to 10 years, investigating each stage of cosmic history – from the first light after the Big Bang to the formation of galaxies, stars, and planets, and finally to the evolution of our own solar system. It will significantly advance our understanding of the Universe and the origins of life.

10

MATHEMATICS



2024 RESEARCH FRONTS

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN MATHEMATICS

The Top 10 Research Fronts in mathematics mainly include: stability and robustness in data-driven model predictive control; augmented synthetic control method; Gaussian process optimization methods and applications in big data environments; knockoff filter for high-dimensional selective inference; deep learning algorithms for solving partial differential equations; statistical inference and optimal transport using Wasserstein distance; applications of deep neural networks in high-dimensional data processing and function approximation; multiple model application of scalar auxiliary variable (SAV) methods; sparse modeling and optimal control of high-dimensional dynamic systems; and new algorithms for optimal transmission problems and applications.

In 2024, the Top 10 fronts show both continuity and new development compared with the fronts selected in previous years. Research on the properties and solutions of partial differential equations and several fronts in the field of nonlinear systems have been consecutively selected among the hot or emerging Research Fronts in past years. In 2024, new algorithms and applications for optimal transmission problems stand out as a highlight of research in this area.

Table 46: Top10 Research Fronts in mathematics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Stability and robustness in data-driven model predictive control	6	533	2021.0
2	Augmented synthetic control method	9	905	2020.3
3	Gaussian process optimization methods and applications in big data environments	6	584	2019.8
4	Knockoff filter for high-dimensional selective inference	8	614	2019.4
5	Deep learning algorithms for solving partial differential equations	9	7300	2019.2
6	Statistical inference and optimal transport using Wasserstein distance	2	232	2019.0
7	Applications of deep neural networks in high-dimensional data processing and function approximation	3	331	2018.7
8	Multiple model application of scalar auxiliary variable (SAV) methods	6	1230	2018.5
9	Sparse modeling and optimal control of high-dimensional dynamic systems	3	303	2018.3
10	New algorithms for optimal transmission problems and applications	3	240	2018.0

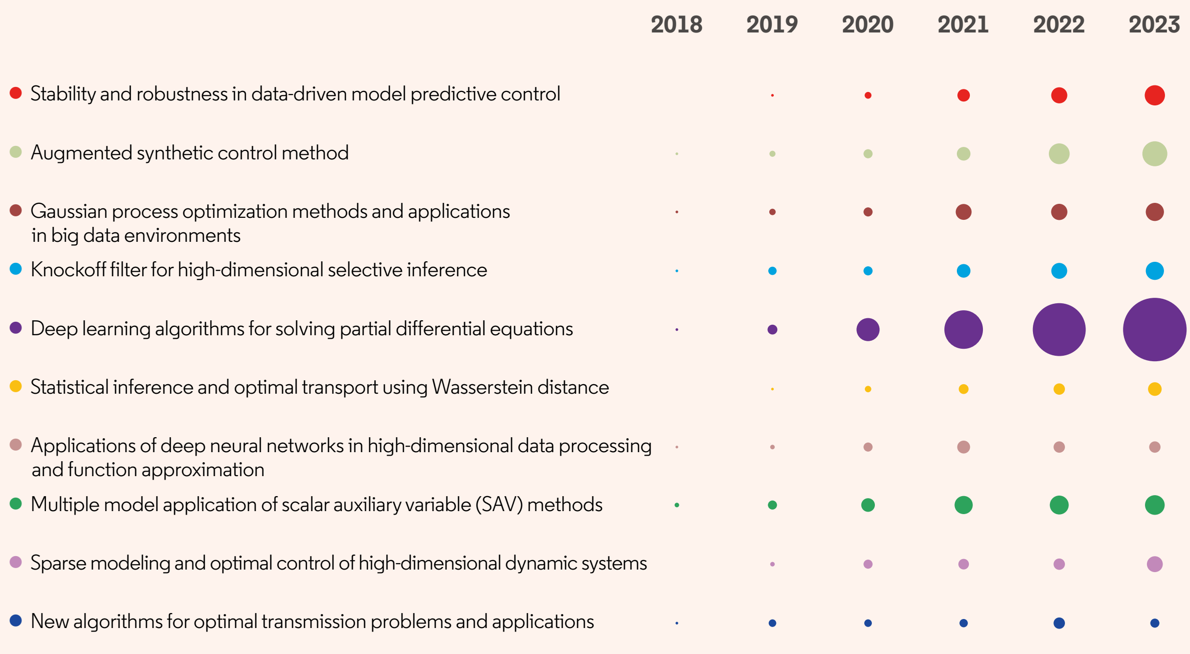


Figure 25: Citing papers for the top 10 Research Fronts in mathematics

1.2 KEY HOT RESEARCH FRONT — "Stability and robustness in data-driven model predictive control"

Model predictive control (MPC) is a technique that uses mathematical models to optimize control systems in real-time over a finite horizon. Originating in the 1970s from the combination of control theory and optimization methods, MPC was initially applied primarily in industrial process control and chemical engineering. The technique aims to optimize current control strategies by predicting future system behavior to improve system stability and responsiveness. With advances in computing power and mathematical modeling techniques, MPC has gradually expanded into a wider range of application areas, such as traffic control, energy management, mechanical systems, and biomedical engineering.

Traditional MPC methods often rely on precise mathematical models of the system, which require precise system descriptions and parameters. This poses challenges in practical applications. With the rise of data science and machine learning, data-driven approaches have become the focus of research. Using real-time data and machine learning techniques, data-driven MPC can flexibly adapt to the dynamic changes of complex systems, bringing new directions and possibilities to the development of control theory.

Research on stability and robustness, as a core issue of data-driven MPC, focuses on maintaining desired control performance in the face of dynamic changes, measurement noise, and parameter uncertainty. This not only deepens the theoretical understanding of control-system stability but also helps to develop new optimization techniques and robust control strategies. In summary, the research direction of this front can provide important theoretical support for the design and implementation of automated control systems. This research not only advances the forefront of control theory but also enhances its significant application potential in cutting-edge fields such as autonomous driving and smart manufacturing.

This hot Research Front includes six core papers that focus on various control strategies, stability and robustness guarantees, theoretical analysis, and application validation. Specifically, these papers cover various data-driven control methods, such as implicit model representation, linear matrix inequalities (LMI), and applications of random matrix theory. These methods are not only applicable to linear time-invariant systems, but also extend to nonlinear systems and control in uncertain environments. They emphasize the design of data-driven MPC schemes with strong stability and robustness by incorporating regularization and optimization methods that achieve practical exponential stability in closed-loop systems under measurement noise and model uncertainty, thereby increasing the reliability of control systems. This work not only theoretically demonstrated the feasibility of these control schemes but also verified their effectiveness in practical applications through numerous numerical experiments and case studies. the feasibility of the control scheme but also verified its effectiveness in practical applications numerical experiments and case studies.

In addition, these core papers reflect a trend of interdisciplinary integration within this hot front, particularly in dealing with dynamic uncertainties and complex environments. The papers also show the intersection of data-driven control techniques with emerging methods such as reinforcement learning. This provides new ideas and solutions for the future of intelligent and adaptive control systems. Future research will also focus on further improving the practicality and universality of data-driven control techniques.

Notably, the three most-cited core papers in this front represent key innovative studies that propose data-driven control strategies while reducing reliance on precise system models, thereby significantly improving the stability and robustness of control systems under uncertainty and noise. Specifically, the strategies use historical input-output data and persistent excitation data to construct implicit model representations and parameterization methods without explicit system matrix identification. Theoretical proofs validate the exponential stability of closed-loop systems under both noisy and noise-free conditions, while robust modification schemes incorporating relaxation variables and regularization terms enhance the system's resilience to perturbations. Furthermore, the integration of reinforcement learning with control theory explores the critical role of the model in reinforcement learning algorithms, providing new insights for the design of control strategies in complex environments. These contributions provide a new theoretical and methodological foundation for research on the stability and robustness of data-driven model predictive control, advancing the field and having significant implications for both theoretical research and engineering applications.

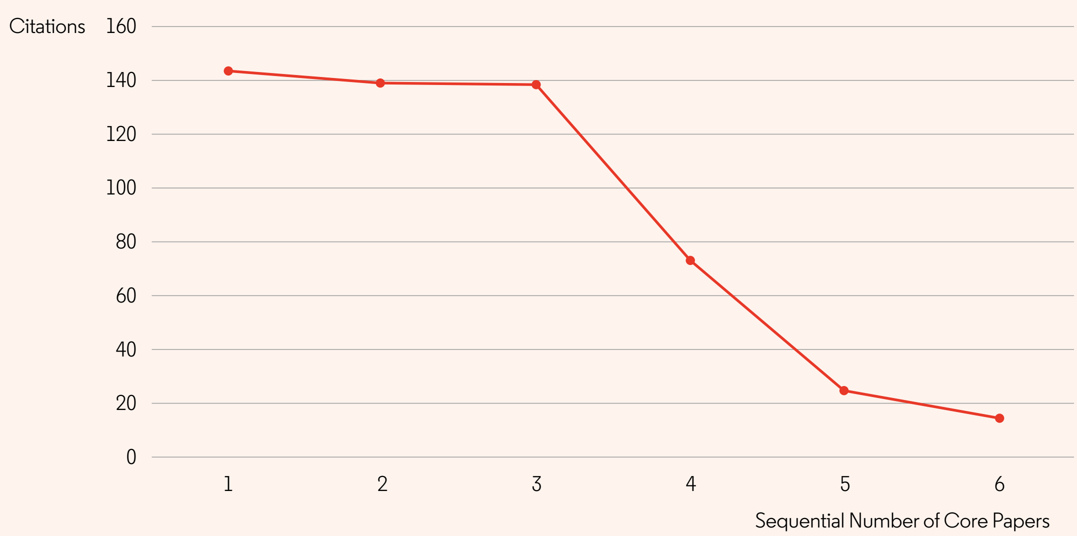


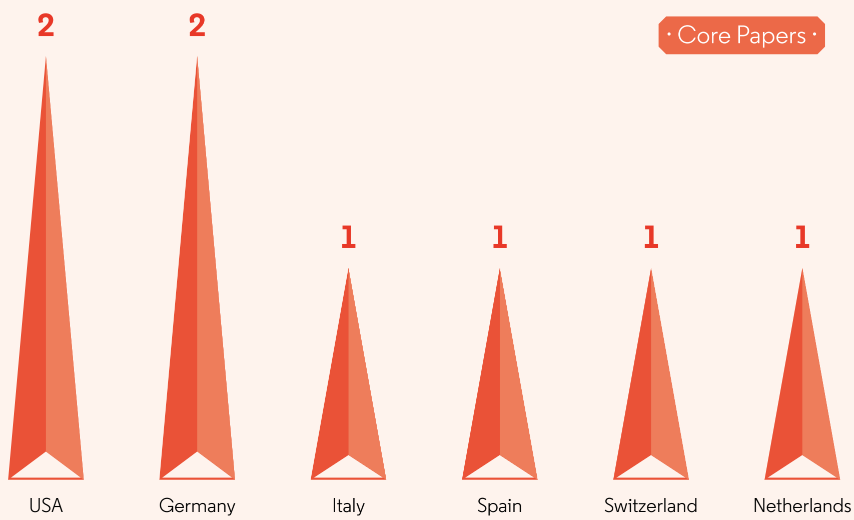
Figure 26: Citation frequency distribution curve of core papers in the Research Front “Stability and robustness in data-driven model predictive control”

In terms of countries producing the core papers (Table 47), both the USA and Germany contributed two core papers each, while Italy, Spain, Switzerland, and the Netherlands each contributed to one core paper. At the institutional level, the University of Stuttgart in Germany and the University of California, Berkeley in the USA each contributed two core papers. Additionally, eight other institutions from Spain, Germany, the USA, Italy, Switzerland, and the Netherlands each contributed one core paper.

Table 47: Top countries and institutions producing core papers in the Research Front "Stability and robustness in data-driven model predictive control"

Country Ranking	Country	Core Papers	Proportion
1	USA	2	33.3%
1	Germany	2	33.3%
3	Italy	1	16.7%
3	Spain	1	16.7%
3	Switzerland	1	16.7%
3	Netherlands	1	16.7%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of Stuttgart	Germany	2	33.3%
1	University of California, Berkeley	USA	2	33.3%
3	University of Florence	Italy	1	16.7%
3	Ctr Int Metodes Numer Engin	Spain	1	16.7%
3	Swiss Federal Institute of Technology Zurich	Switzerland	1	16.7%
3	Leibniz University of Hannover	Germany	1	16.7%
3	University of Groningen	Netherlands	1	16.7%
3	Institut Catala de Recerca Avancada	Spain	1	16.7%
3	University of Polytech Catalunya	Spain	1	16.7%
3	California Institute of Technology	USA	1	16.7%



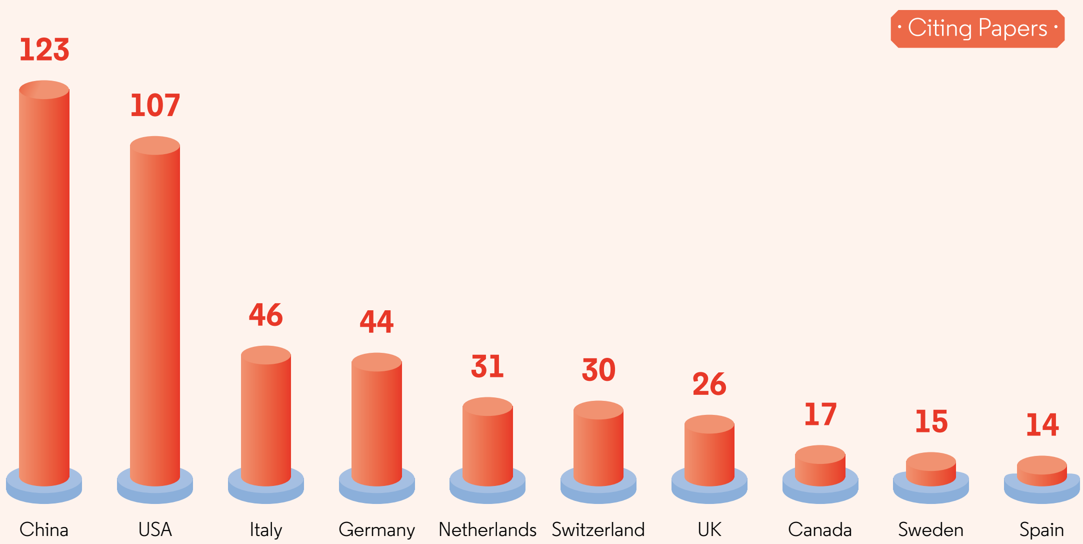
From the perspective of citing papers in this Research Front (Table 48), China is the most active country in tracking and advancing research in this area, producing 123 citing reports at this writing. The USA ranks 2nd with 107 citing papers. Aside from China and the USA, Italy, Germany, the Netherlands, and Switzerland fall into the second tier in output of citing papers, with a production range of 30 to 50 papers; they are also among the top producing countries for core papers.

Among the top institutions producing citing papers, the Swiss Federal Institute of Technology in Zurich ranks 1st with 25 papers, followed by the University of Stuttgart in Germany and the University of Groningen in the Netherlands, which occupy the 2nd and 3rd places, respectively. Notably, both China and Italy have three institutions on the list, making them the countries with the highest number of top institutions. China's listed institutions include Shanghai Jiao Tong University, Beijing Institute of Technology, and Tongji University. Additionally, institutions such as the University of California, Berkeley, and the Massachusetts Institute of Technology from the USA also made the list.

Table 48: Top countries and institutions producing citing papers in the Research Front "Stability and robustness in data-driven model predictive control"

Country Ranking	Country	Citing Papers	Proportion
1	China	123	30.4%
2	USA	107	26.4%
3	Italy	46	11.4%
4	Germany	44	10.9%
5	Netherlands	31	7.7%
6	Switzerland	30	7.4%
7	UK	26	6.4%
8	Canada	17	4.2%
9	Sweden	15	3.7%
10	Spain	14	3.5%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Swiss Federal Institute of Technology Zurich	Switzerland	25	6.2%
2	University of Stuttgart	Germany	21	5.2%
3	University of Groningen	Netherlands	20	4.9%
4	Polytechnic University of Milan	Italy	15	3.7%
5	University of California, Berkeley	USA	14	3.5%
6	Shanghai Jiao Tong University	China	12	3.0%
6	University of Florence	Italy	12	3.0%
8	Beijing Institute of Technology	China	10	2.5%
8	Tongji University	China	10	2.5%
10	Leibniz University of Hannover	Germany	9	2.2%
10	Massachusetts Institute of Technology (MIT)	USA	9	2.2%
10	University of Oxford	UK	9	2.2%
10	University of Padua	Italy	9	2.2%



1.3 KEY HOT RESEARCH FRONT — "New algorithms for optimal transmission problems and applications"

The optimal transport problem was first introduced in 1781 by the French mathematician Gaspard Monge. The object is to move a given quantity of sand from one pile to another target pile with a specified shape while minimizing the amount of work. The goal of the optimal transport problem is to find an optimal transport map between two probability distributions at the lowest global cost (the so-called Monge map).

In 1942, the former Soviet mathematician Leonid Kantorovich, a Nobel Laureate in Economics, reformulated the optimal transport problem, based on his study of resource allocation and national economic optimization problems before and after World War II. His formulation allows the mass of a location to be transported separately to multiple destinations. Therefore, many problems can be transformed from the Monge problem of finding the optimal transport map to the Kantorovich problem of finding the optimal transport plan. This linear programming problem can be solved using methods such as network simplex algorithms.

In 1991, the French mathematician Yann Brenier first established the equivalence between the continuous forms of the Monge problem and the Kantorovich problem. This advance in understanding the optimal transport of continuous distribution problems allows the definition of transport problems between arbitrary probability measures, thus advancing the theory of optimal transport.

In 2013, another French mathematician, Marco Cuturi, introduced entropy regularization to constrain the optimal transport distance. He reformulated the optimal transport problem as a convex optimization problem and developed the Sinkhorn algorithm. This algorithm significantly increased the speed of solving optimal transport problems while maintaining a satisfactory level of accuracy in the optimal transport distance. Mathematicians Cédric Villani and Alessio Figalli received the Fields Medal in, respectively, 2010 and 2018 for their substantial contributions to optimal transport theory and its applications in areas such as partial differential equations, metric geometry, and probability.

While the optimal transport problem originated from an engineering challenge, its robust scalability across different contexts has led to extensive applications in fields as diverse as logistics and transportation in economics and operations research, color, and texture conversion in computer graphics, as well as fluid dynamics and statistical mechanics. More recently, the concepts and methods of optimal transport theory have increasingly influenced machine learning, with significant impact in areas such as image matching using deep learning, computational fluid dynamics, economics, and medicine.

The hot Research Front "New algorithms for optimal transmission problems and applications" contains three core papers that highlight significant advances in both the theoretical and applied research of the optimal transport problem. One paper presents an extension of the Sinkhorn algorithm, resulting in a new fast algorithm for approximating the non-equilibrium optimal transport problem. The method is validated by applications to two-dimensional shape modification, color transfer, and growth models. The second paper develops a comprehensive theory for the optimal transport problem between non-negative and finite Radon measures in general topological spaces. The third paper defines a new transport metric on the space of non-negative measures, generalizes optimal transport to metrics with different properties, and verifies the application of this algorithm in image interpolation.

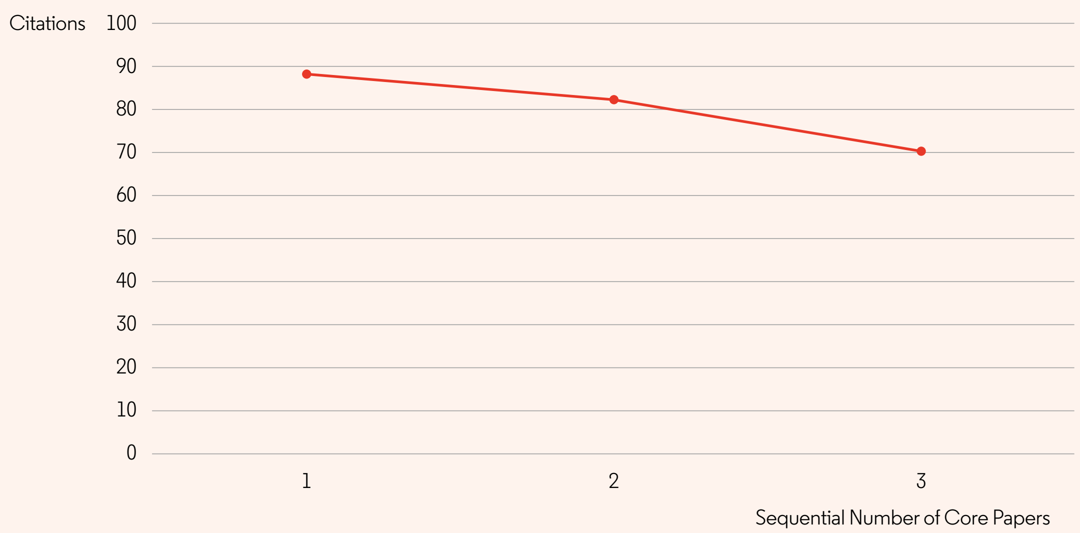


Figure 27: Citation frequency distribution curve of core papers in the Research Front "New algorithms for optimal transmission problems and applications"

Looking at the distribution of countries and institutions producing the core papers for this front (Table 49), France independently contributed two core papers, with authors mainly from Universite PSL, one of the world's leading centers for pure and applied mathematics research. Germany and Italy jointly contributed another core paper in this hot front, featuring authors based in Germany at the Weierstrass Institute and the Humboldt University of Berlin, and in Italy at the University of Pavia.

Table 49: Top countries and institutions producing core papers in the Research Front "New algorithms for optimal transmission problems and applications"

Country Ranking	Country	Core Papers	Proportion
1	France	2	66.7%
2	Germany	1	33.3%
2	Italy	1	33.3%

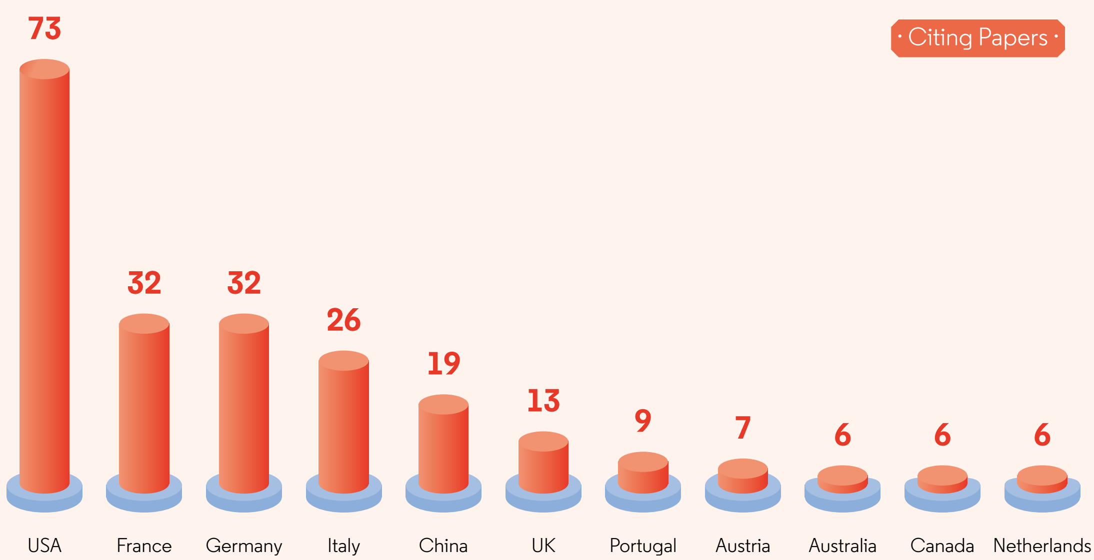
Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	National Center for Scientific Research of France (CNRS)	France	2	66.7%
1	Universite PSL	France	2	66.7%
3	Weierstrass Institute for Applied Analysis and Stochastics	Germany	1	33.3%
3	INRIA	France	1	33.3%
3	École Normale Supérieure Paris-Saclay	France	1	33.3%
3	Humboldt-Universität zu Berlin	Germany	1	33.3%
3	University of Pavia	Italy	1	33.3%

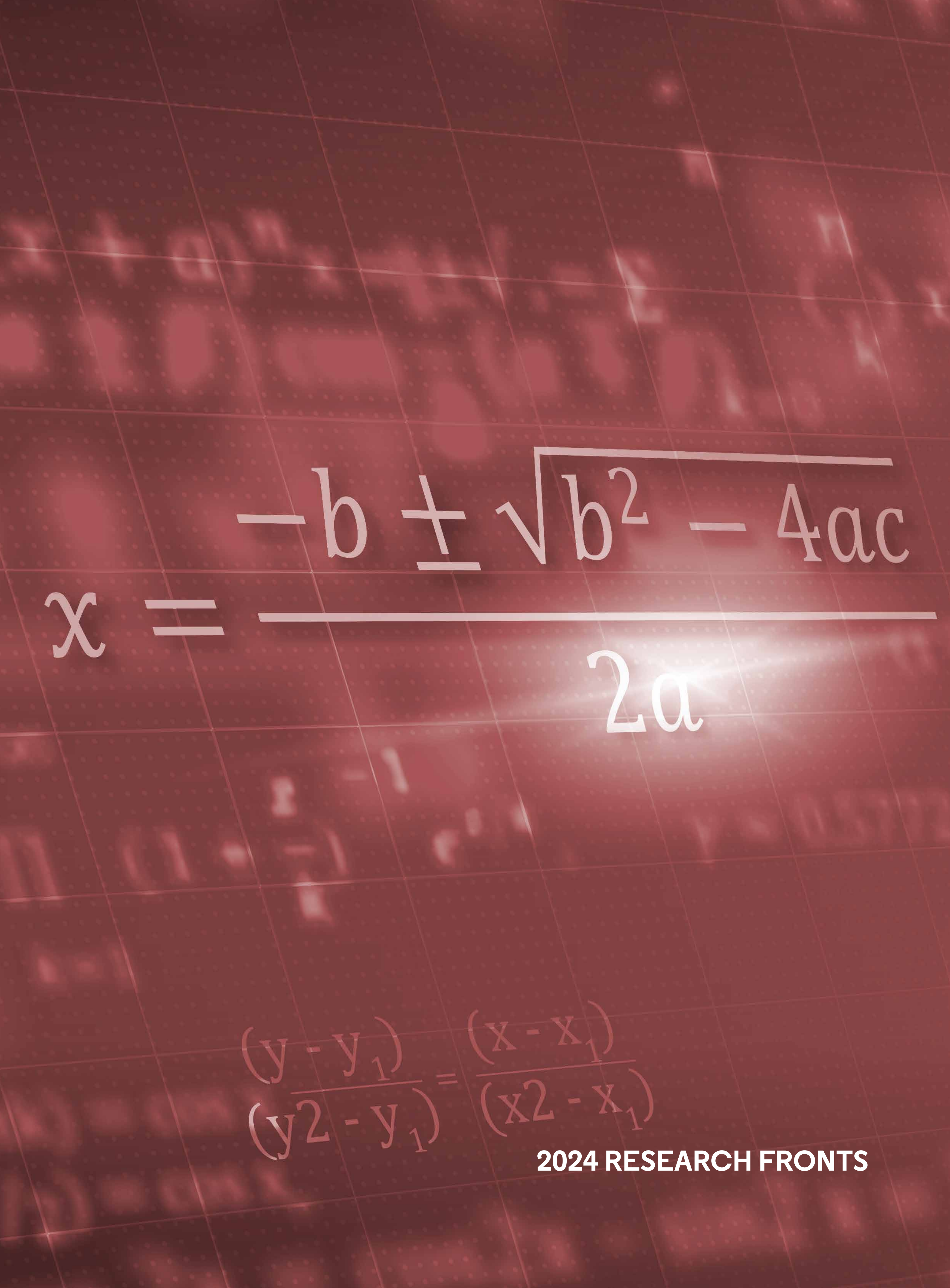
In terms of the citing papers (Table 50), the USA is in the leading position, contributing 40.1% of all citing papers. France, Germany, and Italy rank 2nd, 3rd and 4th, respectively. China is also actively following up on this Research Front. Among the top citing institutions, research institutions in France and the USA hold five and three positions, respectively. Notable contributing institutions with high participation include the French National Center for Science Research (CNRS), University of Paris Cite, University of Paris Saclay, MIT, and the University of California, Los Angeles.

Table 50: Top countries and institutions producing citing papers in the Research Front "New algorithms for optimal transmission problems and applications"

Country Ranking	Country	Citing Papers	Proportion
1	USA	73	40.1%
2	France	32	17.6%
2	Germany	32	17.6%
4	Italy	26	14.3%
5	China	19	10.4%
6	UK	13	7.1%
7	Portugal	9	4.9%
8	Austria	7	3.8%
9	Australia	6	3.3%
9	Canada	6	3.3%
9	Netherlands	6	3.3%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	National Center for Scientific Research of France (CNRS)	France	20	11.0%
2	Massachusetts Institute of Technology (MIT)	USA	11	6.0%
2	University of Paris Cite	France	11	6.0%
2	University of Paris Saclay	France	11	6.0%
5	University of California, Los Angeles	USA	10	5.5%
6	University of California, Irvine	USA	8	4.4%
6	University of Padua	Italy	8	4.4%
8	INRIA	France	7	3.8%
8	Technical University of Munich	Germany	7	3.8%





2024 RESEARCH FRONTS

11

INFORMATION SCIENCE

2024 RESEARCH FRONTS

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN INFORMATION SCIENCE

The Top 10 Research Fronts in information science mainly focus on next-generation communication and networks, the theory and applications of artificial intelligence (AI), and innovative design of AI hardware (Table 51). Of the four hot specialty areas centering on next-generation communication and networks, “Integrated sensing and communications” has emerged as a new hot front. Topics surrounding intelligent reflecting surface have appeared among the hot fronts in several previous reports. This time the focus is on “Key technical challenges of intelligent reflecting surface in wireless communication systems such as 6G”. The hot fronts “Energy efficient federated learning over wireless communication networks” and “UAV in future wireless networks and edge computing and its optimized design” continue to evolve and deepen Four hot fronts derive from the theory and application of AI. Among them, “Machine learning-assisted directed protein evolution” and “Deep learning-based person re-identification” have emerged as hot fronts for the first time. Additionally, the theoretical foundations and applications of explainable AI have undergone more in-depth exploration based on last year's front in the same topic. Two hot fronts center on the innovative design of AI hardware. “Fully hardware-implemented memristor efficient neural network” makes its debut as a hot front, and “Hardware design, algorithmic innovation and application of neuromorphic computing” carries forward the hot front on “Spiking neural networks and their neuromorphic chips” from the previous year.

Table 51: Top 10 Research Fronts in information science

Rank	Hot Research Fronts	Core papers	Citations	Mean Year of Core Papers
1	Machine learning-assisted directed protein evolution	19	2990	2020.6
2	Energy efficient federated learning over wireless communication networks	22	5940	2020.4
3	Deep learning-based person re-identification	25	3899	2020.3
4	Integrated sensing and communications	12	1937	2020.3
5	Theoretical foundations and applications of explainable artificial intelligence	17	9871	2019.8
6	Key technical challenges of intelligent reflecting surface in wireless communication systems such as 6G	27	12404	2019.7
7	Deep transfer learning based highly accurate intelligent fault diagnosis	14	4152	2019.4
8	UAV in future wireless networks and edge computing and its optimized design	36	9382	2018.9
9	Hardware design, algorithmic innovation and application of neuromorphic computing	15	4364	2018.9
10	Fully hardware-implemented memristor efficient neural network	10	3684	2018.8

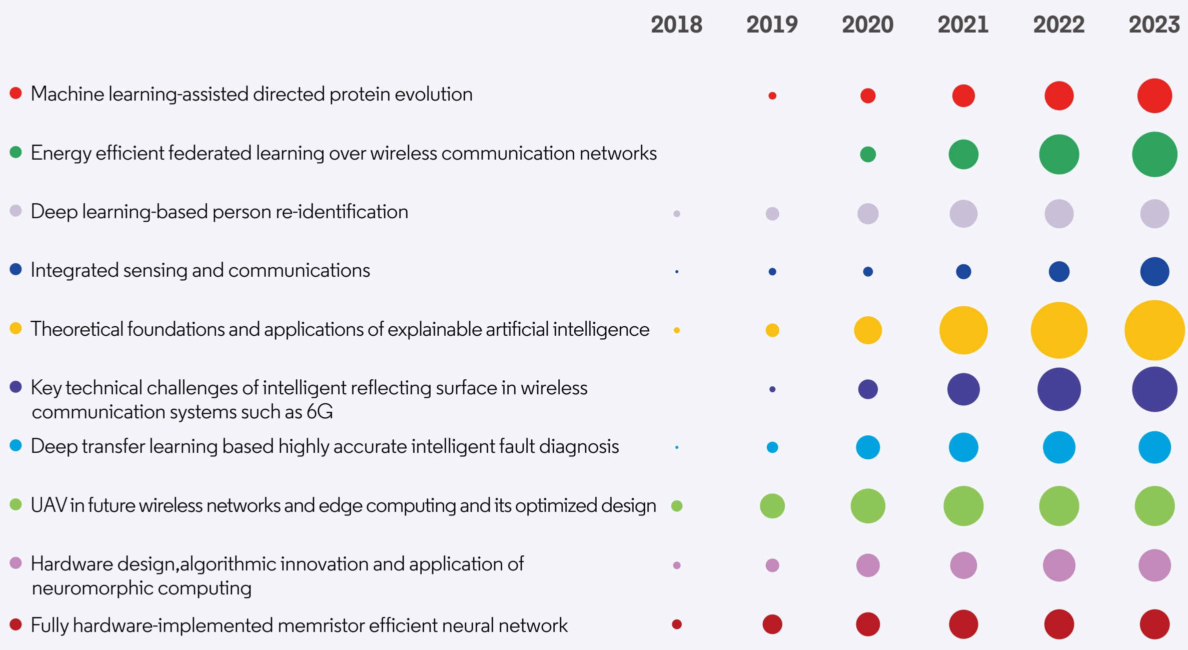


Figure 28: Citing papers for the Top 10 Research Fronts in information science

1.2 KEY HOT RESEARCH FRONT – "Machine learning-assisted directed protein evolution"

In recent years, machine learning-assisted directed protein evolution has emerged as a hot research direction at the intersection of biotechnology and computational science. Leveraging the powerful data processing and predictive capabilities of machine learning algorithms, this approach optimizes and accelerates the process of protein directed evolution, aiming to more efficiently explore the mutational space of protein sequences and design proteins with superior properties. In 2018, Frances H. Arnold of the California Institute of Technology in the USA was awarded the Nobel Prize in Chemistry for inventing the technique of enzyme directed evolution, which significantly enhanced the efficiency of protein engineering modifications for biological enzyme catalysts. However, traditional directed evolution methods suffer from high experimental costs, low screening efficiency, and a tendency to get stuck in local optima. Machine learning-assisted directed protein evolution, by simulating the experimental screening process through computer models, can significantly reduce the burden of experimental screening, improve screening efficiency, and provide new ideas and methodologies for protein engineering.

The key technical methods of machine learning-assisted directed protein evolution include deep neural network models, transfer learning, and multitask learning. Despite the immense potential in applications of machine-learning-assisted protein directed evolution, the field still faces several challenges in practical applications, such as varying data quality, high model complexity, and substantial computational resource requirements. In the future, with the continuous enhancement of computing capabilities and optimization of algorithms, machine learning-assisted directed protein evolution technology will become more mature and refined, providing more efficient and precise solutions for protein engineering.

The hot research front "Machine learning-assisted directed protein evolution" encompasses 19 core papers, primarily discussing the application of machine learning techniques in key domains of protein engineering. These reports cover a series of novel methods and models, such as utilizing deep learning architectures to accurately model the three-dimensional structures and dynamic behaviors of proteins; employing machine learning models to predict the stability and activity of proteins under different environmental conditions, thereby facilitating the discovery of new protein functions; and leveraging machine learning algorithms for efficient design of protein sequences.

The paper titled "Biological structure and function emerge from scaling unsupervised learning to 250 million protein sequences," published in *the Proceedings of the National Academy of Sciences (PNAS)* by Alexander Rives of Facebook AI Research and colleagues, has garnered the highest citation count, surpassing 450 at this writing. This paper applies unsupervised learning to 250 million protein sequences, successfully ascertaining the pertinent biochemical properties and structural information. The technique demonstrates the tremendous potential of unsupervised learning in the field of biology and provides new perspectives and methodologies for protein engineering research.

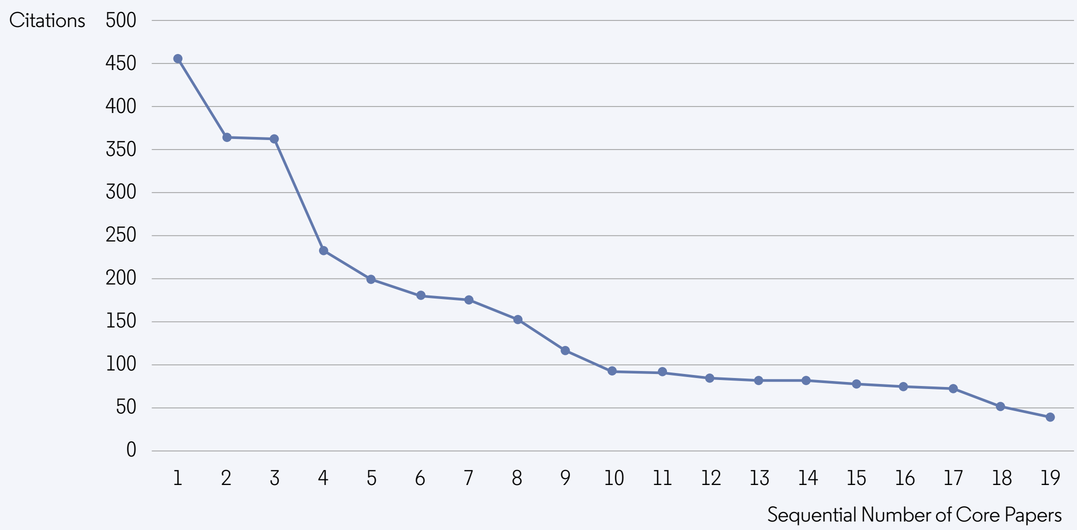


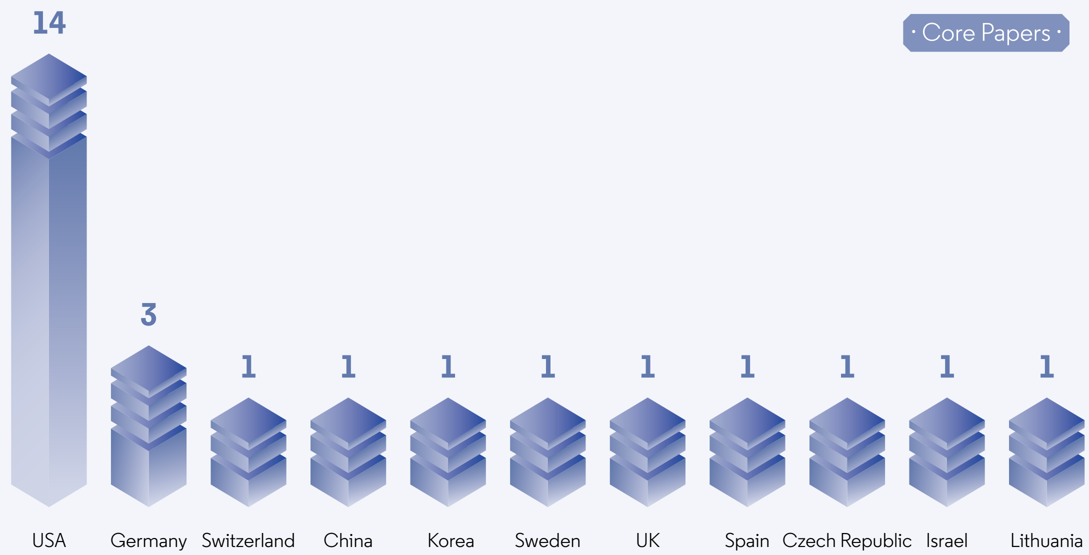
Figure 29: Citation frequency distribution curve of core papers in the Research Front "Machine learning-assisted directed protein evolution"

Among the 19 core papers in this Research Front, the USA contributed 14, reflecting its dominant position in this research direction. Institutions based in Germany contributed three papers, while Switzerland, China, South Korea, Sweden, and other countries each contributed one. In terms of institutions producing the core papers, those in the USA stood out prominently, with Harvard University contributing seven core papers, the Massachusetts Institute of Technology four, and the University of California, Berkeley, Google, Technical University of Munich, University of California, San Francisco, and other institutions each contributing two papers.

Table 52: Top countries and institutions producing core papers in the Research Front of "Machine learning-assisted directed protein evolution"

Country Ranking	Country	Core Papers	Proportion
1	USA	14	73.7%
2	Germany	3	15.8%
3	Switzerland	1	5.3%
3	China	1	5.3%
3	Korea	1	5.3%
3	Sweden	1	5.3%
3	UK	1	5.3%
3	Spain	1	5.3%
3	Czech Republic	1	5.3%
3	Israel	1	5.3%
3	Lithuania	1	5.3%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Harvard University	USA	7	36.8%
2	Massachusetts Institute of Technology	USA	4	21.1%
3	University of California, Berkeley	USA	2	10.5%
3	Google	USA	2	10.5%
3	Technical University of Munich	Germany	2	10.5%
3	University of California, San Francisco	USA	2	10.5%
3	United States Department of Energy	USA	2	10.5%
3	California Institute of Technology	USA	2	10.5%

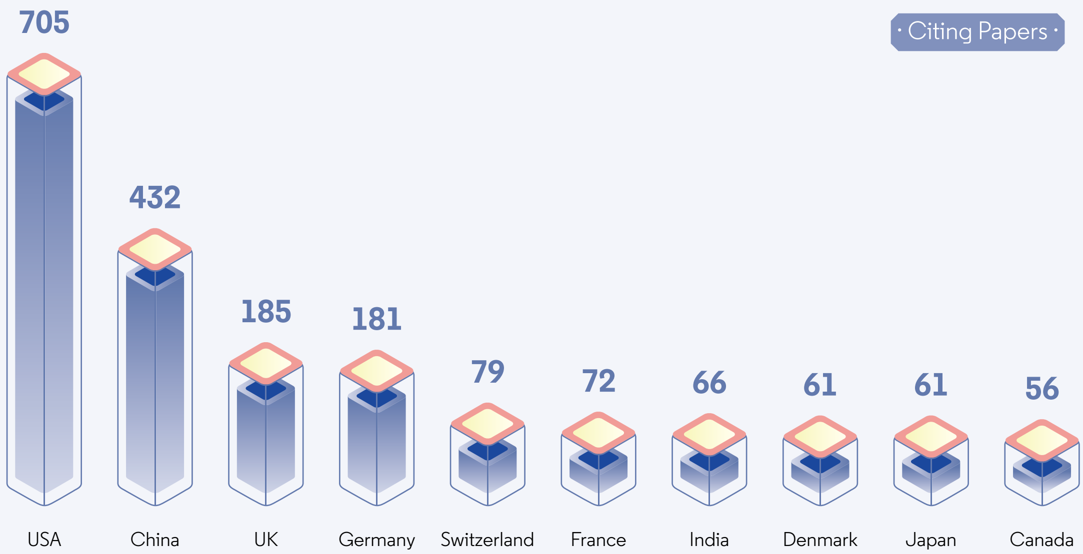


Analysis of the citing papers (Table 53) reveals that the USA has produced the highest number, participating in 705 such reports, accounting for 40.2% of the total, demonstrating its continued attention to this research direction. China follows closely, with 432 citing papers. The contributions from China and the USA together account for 64.8% of the total number of citing papers. The UK, Germany, Switzerland, France, and other countries are subsequent in rank. In terms of citing institutions, Harvard University is the most active, ranking first with 80 papers, followed closely by the Chinese Academy of Sciences and the Massachusetts Institute of Technology (MIT), with 74 and 73 papers respectively. Additionally, Stanford University, the National Centre for Scientific Research of France, the Swiss Federal Institute of Technology (ETH) in Zurich, the University of Cambridge, and other institutions are also major contributors to the citing papers in this Research Front.

Table 53: Top countries and institutions producing citing papers in the Research Front "Machine learning-assisted directed protein evolution"

Country Ranking	country	Citing Papers	proportion
1	USA	705	40.2%
2	China	432	24.6%
3	UK	185	10.5%
4	Germany	181	10.3%
5	Switzerland	79	4.5%
6	France	72	4.1%
7	India	66	3.8%
8	Denmark	61	3.5%
8	Japan	61	3.5%
10	Canada	56	3.2%

Institution Ranking	Institution	Affiliated Country	Citing Papers	proportion
1	Harvard University	USA	80	4.6%
2	Chinese Academy of Sciences	China	74	4.2%
3	Massachusetts Institute of Technology	USA	73	4.2%
4	Stanford University	USA	37	2.1%
5	National Center for Scientific Research of France	France	35	2.0%
6	Swiss Federal Institute of Technology in Zurich	Switzerland	32	1.8%
6	University of Cambridge	UK	32	1.8%
8	Technical University of Munich	Germany	30	1.7%
9	University of California, Berkeley	USA	29	1.7%
10	Denmark University of Technology	Denmark	27	1.5%
10	University of Florida	USA	27	1.5%



1.3 KEY HOT RESEARCH FRONT – "Integrated sensing and communications"

With the development of next-generation wireless communication systems, a variety of emerging applications such as smart cities, intelligent manufacturing, and remote healthcare will become a reality. These applications share a common feature, requiring both high-quality wireless communication capabilities and robust and high-precision sensing capabilities. The increasing scarcity of wireless spectrum resources and the interference in more and more radar bands are driving wireless communication and sensing systems towards higher frequency bands, larger antenna arrays, and miniaturization, which are becoming increasingly similar in terms of hardware architecture, channel characteristics, and signal processing.

This scenario provides an opportunity for utilizing wireless infrastructure for sensing. Therefore, Integrated Sensing and Communications (ISAC) is widely recognized as a key enabling technology for 6G communication networks, which will enable future networks to go beyond traditional communications and provide ubiquitous sensing services to measure and even image the surrounding environment. The technology can share spectrum and hardware platforms between communication and sensing, thus improving the spectral, energy, and hardware efficiency of the system, and even enhancing the performance of both functions through mutual assistance and reinforcement between communication and sensing.

Considerable technical challenges still confront ISAC in terms of fundamental theory, signal processing, and network aspects, such as optimal waveform design and bandwidth requirements, optimal system architecture, and communication and sensing data fusion. As a result, the field has attracted significant attention from both academia and industry.

Twelve core papers underlie this hot Research Front, with research reports and review articles each accounting for half. The research articles mainly explore the transceiver architecture of dual-function radar communication base stations, Multiple-Input Multiple-Output (MIMO) beamforming design, and IEEE 802.11ad-based joint vehicular communication-radar systems. The reviews primarily discuss the application scenarios and basic limitations of ISAC, performance trade-offs between communication and sensing, recent advances in signal models, waveform design, and signal processing techniques, as well as methods and challenges in implementing sensing mobile networks.

Among the 12 core papers, the most cited is a research article (322 citations, Figure 30) published in *IEEE Transactions on Communications* in 2020 by researchers from University College London, Rutgers University, and the University of Southampton. The article proposes a novel transceiver architecture and frame structure for dual-function radar-communication base station operating in the millimeter wave band using hybrid analog-digital beamforming technique, as well as a novel scheme for joint target search and communication channel estimation.

Among the review articles, the most cited has attracted 206 citations at this writing, having been published in *IEEE Journal on Selected Areas in Communications* in 2022 by researchers from Southern University of Science and Technology (China), Beijing University of Posts and Telecommunications, University College London, Chinese University of Hong Kong, Huawei Technologies Co., Weizmann Institute of Science in Israel, and the University of Cassino and Southern Lazio in Italy. The paper comprehensively reviews the background, main application scope, and the latest methods of ISAC.

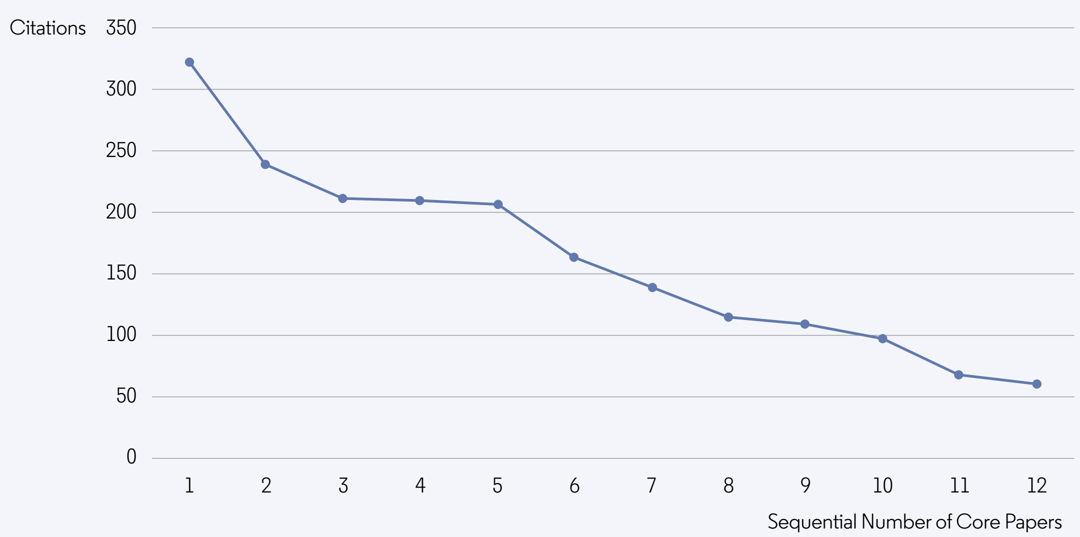


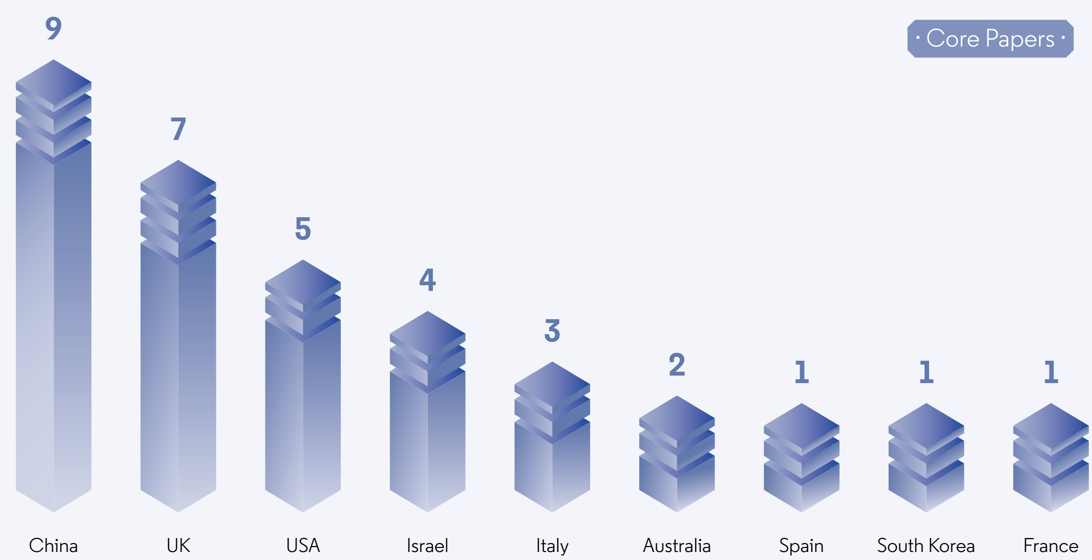
Figure 30: Citation frequency distribution curve of core papers in the Research Front "Integrated sensing and communications"

Among the top countries and institutions producing this front's core papers (Table 54), China demonstrates the highest contribution rate, as its nine papers account for 75.0% of the total, with the UK and the USA ranking 2nd and 3rd. Among the prolific contributing institutions, University College London has performed strongly, ranking 1st, while China's Southern University of Science and Technology ranked 2nd with four papers. The Weizmann Institute of Science in Israel, Rutgers University in the USA, and Beijing University of Posts and Telecommunications in China ranking 3rd. It is evident that, compared to other countries, China, the UK, the USA, and Israel have devoted a heightened level of attention to ISAC research.

Table 54: Top countries and institutions producing core papers in the Research Front "Integrated sensing and communications"

Country Ranking	Country	Citing Papers	Proportion
1	China	9	75.0%
2	UK	7	58.3%
3	USA	5	41.7%
4	Israel	4	33.3%
5	Italy	3	25.0%
6	Australia	2	16.7%
7	Spain	1	8.3%
7	South Korea	1	8.3%
7	France	1	8.3%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University College London	UK	7	58.3%
2	Southern University of Science and Technology	China	4	33.3%
3	Weizmann Institute of Science	Israel	3	25.0%
3	Rutgers University	USA	3	25.0%
3	Beijing University Posts & Telecommunications	China	3	25.0%
7	University of Cassino and Southern Lazio	Italy	2	16.7%
7	University of Southampton	UK	2	16.7%
7	Tsinghua University	China	2	16.7%
7	University of Technology Sydney	Australia	2	16.7%
7	Huawei Technologies Co., Ltd.	China	2	16.7%
7	Beijing Institute of Technology	China	2	16.7%

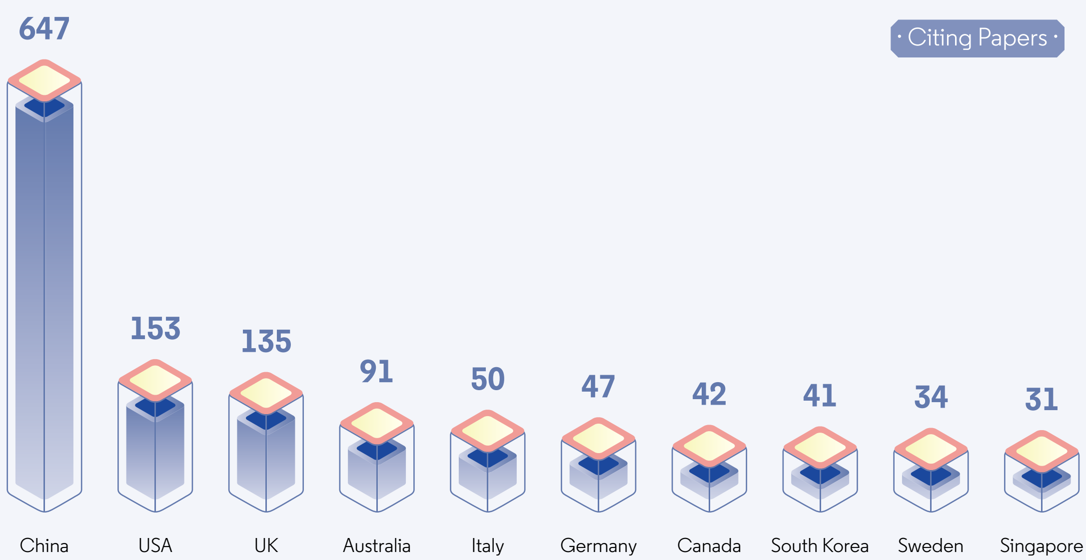


In terms of countries and institutions that cite the core papers in this hot front (Table 55), China is far ahead of other countries, indicating that the nation continues to maintain robust research activity in this area. The USA and the UK form a second tier by the measure of citing papers. In terms of citing institutions, Chinese entities occupy eight of the top 10 seats, and all of them are well-known universities and research institutions. This highlights the strong emphasis that Chinese institutions place on this research direction. Beijing University of Posts and Telecommunications ranked 1st with 74 citing papers, followed by University of Electronic Science and Technology of China and Southern University of Science and Technology. The University of Technology Sydney and University College London have both featured prominently in core papers and citing papers, demonstrating a continuous output in this direction.

Table 55: Top countries and institutions producing citing papers in the Research Front "Integrated sensing and communications"

Country Ranking	Country	Citing Papers	Proportion
1	China	647	67.3%
2	USA	153	15.9%
3	UK	135	14.0%
4	Australia	91	9.5%
5	Italy	50	5.2%
6	Germany	47	4.9%
7	Canada	42	4.4%
8	South Korea	41	4.3%
9	Sweden	34	3.5%
10	Singapore	31	3.2%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	Beijing University Posts & Telecommunications	China	74	7.7%
2	University of Electronic Science and Technology of China	China	67	7.0%
3	Southern University of Science and Technology	China	48	5.0%
3	University of Technology Sydney	Australia	48	5.0%
5	Southeast University	China	45	4.7%
6	Xidian University	China	44	4.6%
7	Beijing Institute of Technology	China	42	4.4%
8	Tsinghua University	China	40	4.2%
9	University College London	UK	38	4.0%
10	Chinese Academy of Sciences	China	30	3.1%



2024 RESEARCH FRONTS

12

ECONOMICS, PSYCHOLOGY AND OTHER SOCIAL SCIENCES

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN ECONOMICS, PSYCHOLOGY AND OTHER SOCIAL SCIENCES

This listing of top 10 hot Research Fronts reflects the intersection and integration of digital and intelligent technologies with economics, psychology and other social sciences, focusing on research trends related to human health, climate, and environmental themes.

Four hot Research Fronts in particular address the direction of the intersection and integration of digital and intelligent technology. Specifically, three fronts – "Application of electroencephalogram (EEG) data analysis in neuroscience, psychology, and cognitive science", "Deep learning algorithms and financial forecasting, asset pricing" and "Algorithms, human resources and platform management for the gig economy" – apply artificial intelligence (AI) and big data technologies and methods to research questions in psychology, economics, and sociology.

The hot front on "Code of ethics for artificial intelligence" conducts theoretical and practical research examining whether the development and application of technology follows ethical standards and social governance requirements.

In terms of human health, climate, and environment topics, three fronts, namely "Impact of COVID-19 on mental health of different demographics", "Research on the relationship between social structural factors and health differences", and "The problem of ultra-processed food consumption", conduct research in the special areas of mental health, food health, and social health.

The two hot Research Fronts "Climate change and investment decision-making" and "The impact of anthropogenic activities on climate change, biodiversity, etc." conduct economic and biodiversity studies from the perspective of climate and environment.

Table 56: Top 10 Research Fronts in economics, psychology and other social sciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Evaluation of policy changes and research on the impact of specific events	30	5871	2021.0
2	Impact of COVID-19 on mental health of different demographics	25	3335	2020.7
3	Climate change and investment decision-making	18	2728	2020.7
4	The impact of anthropogenic activities on climate change, biodiversity, etc.	7	1396	2020.6
5	Research on the relationship between social structural factors and health differences	10	1295	2020.6
6	Application of electroencephalogram (EEG) data analysis in neuroscience, psychology, and cognitive science	8	1217	2020.4
7	Deep learning algorithms and financial forecasting, asset pricing	14	2085	2020.2
8	The problem of ultra-processed food consumption	35	7505	2019.5
9	Algorithms, human resources and platform management for the gig economy	13	2177	2019.2
10	Code of ethics for artificial intelligence	5	1286	2019.2

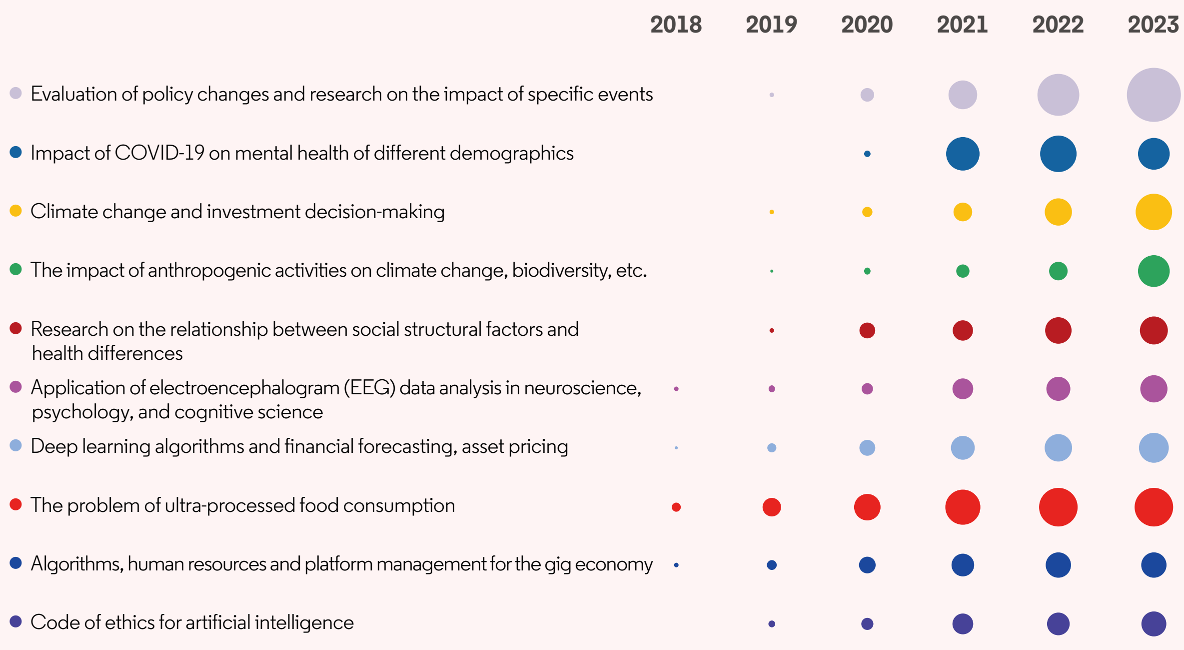


Figure 31: Citing papers for the Top 10 Research Fronts in economics, psychology and other social sciences

1.2 KEY HOT RESEARCH FRONTS - "The problem of ultra-processed food consumption"

Ultra-processed food products are highly sought after for their good taste, convenient access, stable shelf life, and affordability. Today, processed and ultra-processed foods account for over 50% of total dietary energy in high-income countries and a growing number of middle-income countries. However, an increasing number of studies suggest that consumption of ultra-processed food is associated with an increased risk of non-communicable diseases, constituting a public health challenge. In this context, the issue of ultra-processed food consumption has attracted great attention from scientists and scholars, with different studies conducting in-depth analysis on such matters as concept differentiation, disease risk, and social impact.

Among the 35 core papers in this hot front (Figure 32), five report research on the topic of concept differentiation. Nine papers analyze the social impacts of ultra-processed food consumption on population structure, mortality rate, public-health status, and other facets. Twenty-one core papers conduct qualitative and quantitative research on the association between ultra-processed food consumption and non-communicable diseases, with obesity being the most studied.

The most-cited paper specifies what ultra-processed foods are and how to identify them. This report, collaboratively published in *Public Health Nutrition* by researchers at the University of São Paulo in Brazil and the University of Montreal in Canada, has garnered 830 citations at this writing. In providing straightforward guidelines for identifying ultra-processed foods, the report points to the usefulness of checking whether the food's ingredients contain at least one feature of the NOVA ultra-processed food group – i.e., foodstuffs that can be characterized as "industrial formulations" or "synthesized in laboratories," consisting mostly or entirely of substances (e.g., salts, fats, sugars) extracted from foods, rather than drawn directly from natural ingredients.

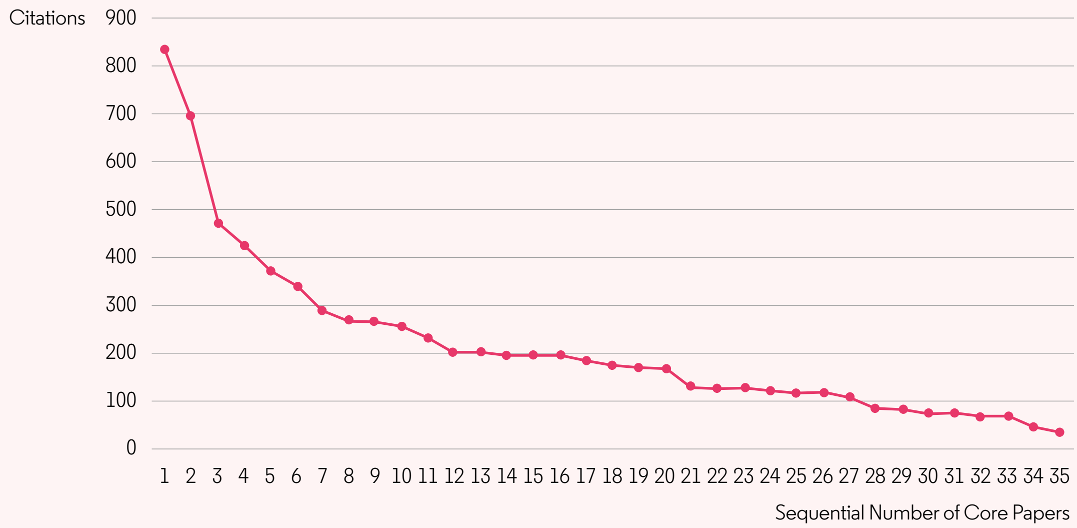


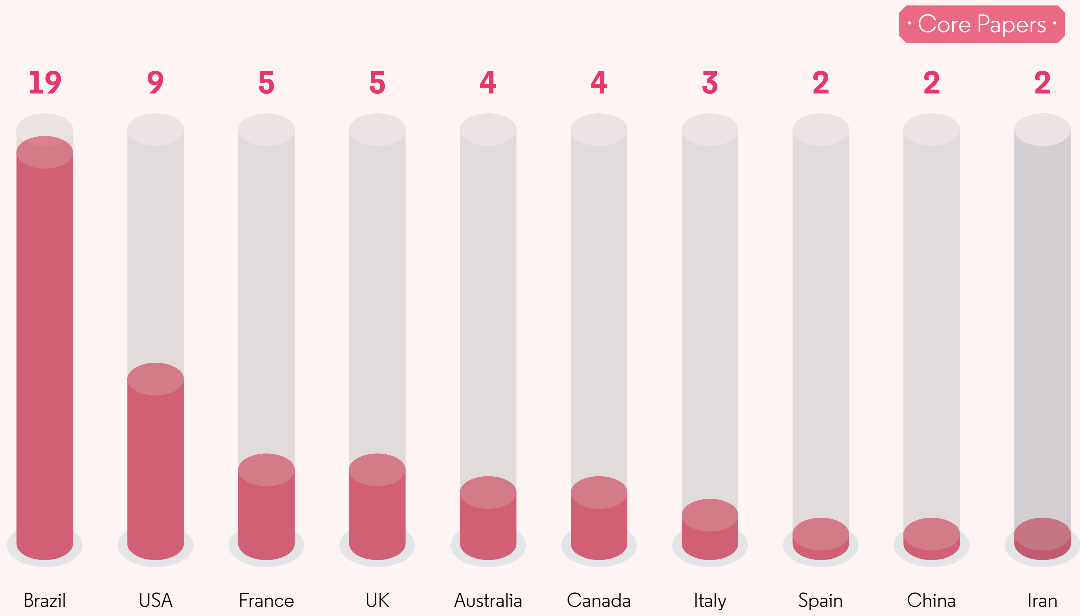
Figure 32: Distribution curve of citation frequency of core papers in the Research Front "The problem of ultra-processed food consumption"

In terms of the countries that are most active in producing core papers, Brazil ranks 1st with 19 foundational reports, accounting for 54.3% of all papers, while the USA, France, and the UK also demonstrate heightened activity in this specialty. China contributes two papers, ranking 8th. Among the top institutions, seven are based in France. The top-ranking institution is the University of São Paulo in Brazil (Table 57).

Table 57: Top countries and institutions producing core papers in the Research Front "The problem of ultra-processed food consumption"

Country Ranking	Country	Core Papers	Proportion
1	Brazil	19	54.3%
2	USA	9	25.7%
3	France	5	14.3%
3	UK	5	14.3%
5	Australia	4	11.4%
5	Canada	4	11.4%
7	Italy	3	8.6%
8	Spain	2	5.7%
8	China	2	5.7%
8	Iran	2	5.7%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of Sao Paulo	Brazil	17	48.6%
2	University of Paris Cite	France	5	14.3%
2	Conservatoire National des Arts et Metiers	France	5	14.3%
2	HESAM University	France	5	14.3%
2	National Research Institute for Agriculture, Food and Environment	France	5	14.3%
2	Assistance Public Hospital Paris	France	5	14.3%
2	National Institute of Health and Medical Research (INSERM)	France	5	14.3%
8	New York University	USA	4	11.4%
8	Deakin University	Australia	4	11.4%
8	University Paris XIII	France	4	11.4%
8	University of Montreal	Canada	4	11.4%

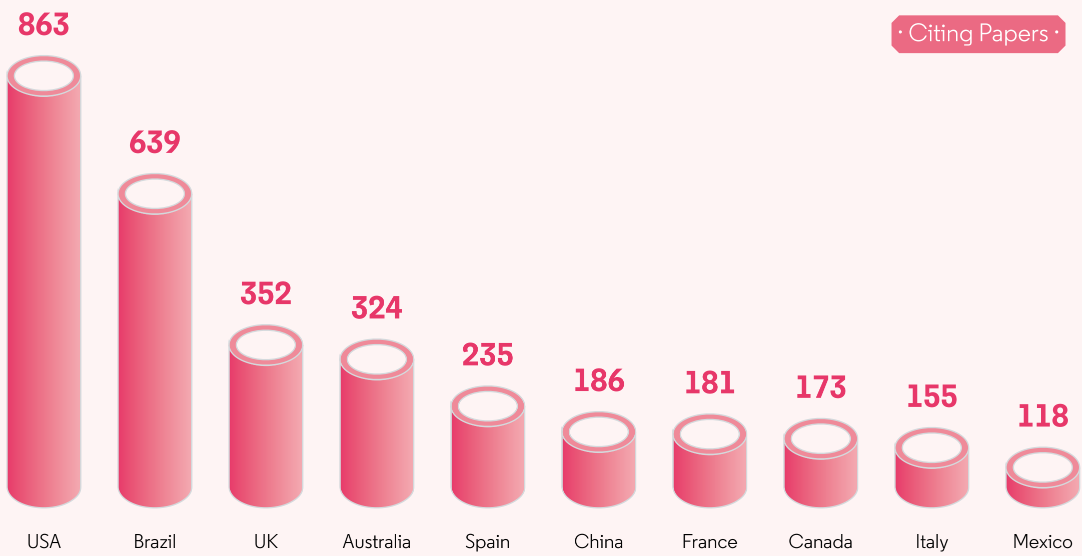


In terms of papers that cite the core literature in this front, the USA ranks 1st with 863 citing papers, followed by Brazil, the UK, and Australia. At the level of citing institutions, the University of São Paulo in Brazil, which produced the most core papers, has also contributed the most numerous citing papers, reflecting the institution's sustained attention and influence in the matter of ultra-processed food. Rounding out the top three by this measure are Harvard University in the USA and Deakin University in Australia.

Table 58: Top countries and institutions producing citing papers in the Research Front "The problem of ultra-processed food consumption"

Country Ranking	Country	Citing Papers	Proportion
1	USA	863	30.1%
2	Brazil	639	22.3%
3	UK	352	12.3%
4	Australia	324	11.3%
5	Spain	235	8.2%
6	China	186	6.5%
7	France	181	6.3%
8	Canada	173	6.0%
9	Italy	155	5.4%
10	Mexico	118	4.1%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	University of Sao Paulo	Brazil	293	10.2%
2	Harvard University	USA	154	5.4%
3	Deakin University	Australia	125	4.4%
4	CIBER	Spain	107	3.7%
5	National Research Institute for Agriculture, Food and Environment	France	94	3.3%
6	University of North Carolina	USA	85	3.0%
7	University of Paris Cite	France	79	2.8%
8	National Institute of Health and Medical Research (INSERM)	France	78	2.7%
9	University of Sydney	Australia	76	2.6%
10	National Institute of Public Health of Mexico	Mexico	70	2.4%
10	Univ Fed Minas Gerais	Brazil	70	2.4%



1.3 KEY HOT RESEARCH FRONT - "Algorithms, human resources and platform management for the gig economy"

The advent of the Internet era has spawned a new form of employment represented by the gig economy, which has fundamentally altered the traditional employment relationship. The gig economy, which relies on rapidly developing digital platforms and differs from traditional employment models, has become a booster for flexible work arrangements and a reservoir for inclusive employment opportunities for all citizens.

A salient feature of the gig economy is that algorithms replace humans in the real-time, dynamic, and automatic control of the task process of workers. The characteristics of this algorithmic control have subsequently brought changes to human resources and platform management. Hence the related research hotspots are mainly concentrated in those aspects.

Thirteen core papers underlie this hot Research Front. Among these, four reports involve research on autonomy, dependence, and instability in the gig economy deriving from algorithmic control. Four papers explore the labor process, personalized work identity, the transformation of the working environment, and other issues in the gig economy as it pertains to human resource management. Five papers focus on the study of platform management in the gig economy, examining such specifics as platform crowdfunding, platform organizational structure, and platform competitiveness.

This front's most-cited foundational paper is a study of autonomy and algorithm control in the global gig economy, published in *Work, Employment and Society* by researchers at the Oxford Internet Institute in the UK, with 372 citations at this writing. This paper reports research on the quality of odd jobs on online labor platforms, especially focusing on the impact of platform algorithm control on gig work. It studied how gig work is controlled and shaped by platform-based algorithms through semi-structured interviews and cross-regional surveys conducted in six countries.

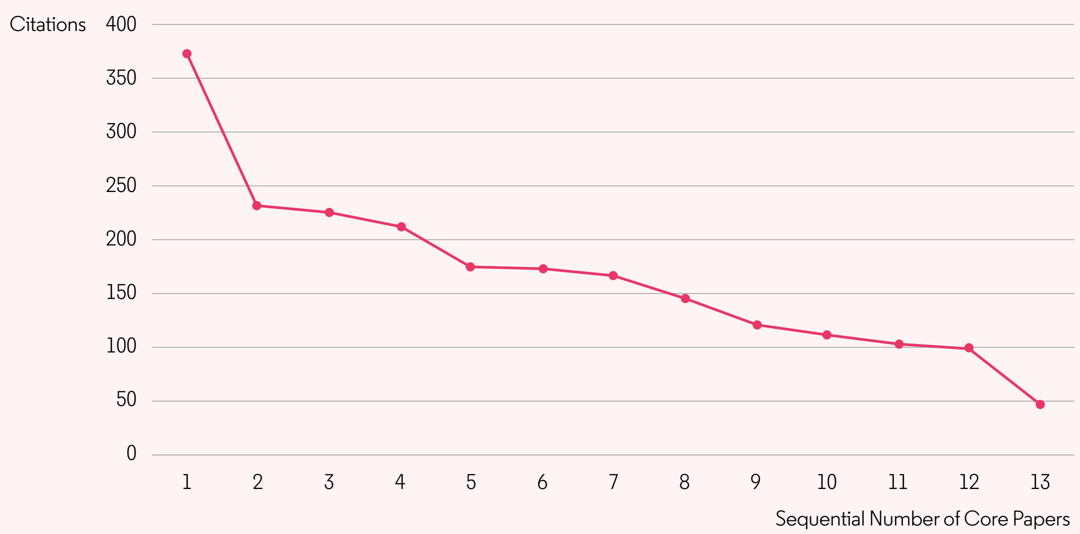


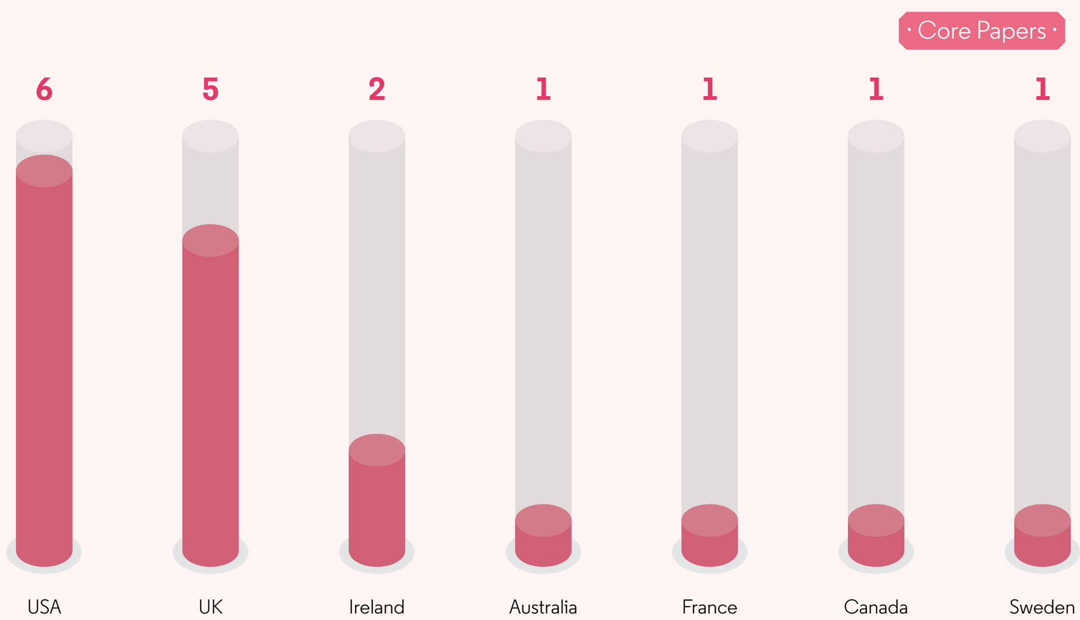
Figure 33 Citation frequency distribution curve of core papers in the Research Front "Algorithms, human resources and platform management for the gig economy"

In terms of the top-producing countries for core papers (Table 59), the USA contributed six foundational reports, accounting for 46.2% of all, followed by the UK with five papers, or 38.5%. Related research has also registered from institutions in Ireland, Australia, France, Canada, and Sweden. At the institutional level, 10 of the top 22 institutions are based in the USA. Sharing the top tier are three entities: In the USA, Boston College and the University of Michigan, along with the University of Oxford in the UK (Table 59).

Table 59: Top countries and institutions producing core papers in the Research Front "Algorithms, human resources and platform management for the gig economy"

Country Ranking	Country	Core Papers	Proportion
1	USA	6	46.2%
2	UK	5	38.5%
3	Ireland	2	15.4%
4	Australia	1	7.7%
4	France	1	7.7%
4	Canada	1	7.7%
4	Sweden	1	7.7%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	University of Oxford	UK	2	15.4%
1	Boston College	USA	2	15.4%
1	University of Michigan	USA	2	15.4%
4	Yale University	USA	1	7.7%
4	Augustana college	USA	1	7.7%
4	University of Illinois Urbana-Champaign	USA	1	7.7%
4	Northeastern University	USA	1	7.7%
4	University of Pennsylvania	USA	1	7.7%
4	Miami University	USA	1	7.7%
4	Harvard University	USA	1	7.7%
4	Fairfield University	USA	1	7.7%
4	University of Warwick	UK	1	7.7%
4	Kings College London	UK	1	7.7%
4	University of Manchester	UK	1	7.7%
4	Edith Cowan University	Australia	1	7.7%
4	University of Sydney	Australia	1	7.7%
4	University of Western Australia	Australia	1	7.7%
4	University of Manitoba	Canada	1	7.7%
4	McMaster University	Canada	1	7.7%
4	University College Cork	Ireland	1	7.7%
4	University College Dublin	Ireland	1	7.7%
4	Lulea University of Technologies	Sweden	1	7.7%

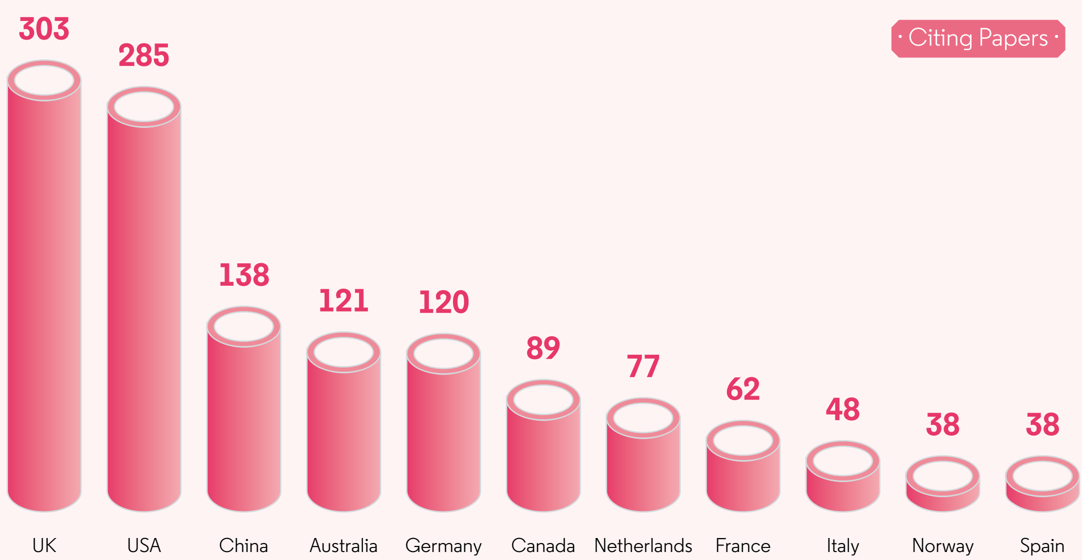


From the perspective of citing papers, the UK ranks 1st with 303 reports, accounting for 25.8% of the total, followed by the USA with 285 (24.2%) and China with 138 (11.7%). In terms of citing institutions, the University of Oxford ranks 1st, with the University of North Carolina and the University of Toronto tied for 2nd place. Renmin University of China and the Copenhagen Business School in Denmark both contributed 17 citing papers, tying for 9th place.

Table 60: Top countries and institutions producing citing papers in the Research Front "Algorithms, human resources and platform management for the gig economy"

Country Ranking	Country	Citing Papers	Proportion
1	UK	303	25.8%
2	USA	285	24.2%
3	China	138	11.7%
4	Australia	121	10.3%
5	Germany	120	10.2%
6	Canada	89	7.6%
7	Netherlands	77	6.5%
8	France	62	5.3%
9	Italy	48	4.1%
10	Norway	38	3.2%
10	Spain	38	3.2%

Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	University of Oxford	UK	39	3.3%
2	University of North Carolina	USA	28	2.4%
2	University of Toronto	Canada	28	2.4%
4	University of Sydney	Australia	21	1.8%
5	BI Norwegian Business School	Norway	20	1.7%
5	Erasmus University Rotterdam	Netherlands	20	1.7%
7	University of Edinburgh	UK	19	1.6%
8	Cornell University	USA	18	1.5%
9	Copenhagen Business School	Denmark	17	1.4%
9	Renmin University of China	China	17	1.4%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN ECONOMICS, PSYCHOLOGY AND OTHER SOCIAL SCIENCES

One research area in the field of economics, psychology and other social sciences has been selected as an emerging Research Front, namely “Application of generative AI technology in education and its impact”.

Table 61: Emerging Research Fronts in economics, psychology and other social sciences

No.	Emerging Research Fronts	Core papers	Number of citations	Average publication year of core papers
1	Application of generative AI technology in education and its impact	15	257	2023.0

2.2 KEY EMERGING RESEARCH FRONT – “Application of generative AI technology in education and its impact”

As the wave of AI sweeps across the globe, the application of generative AI in education is increasingly pioneering reform. This technology, with its outstanding modeling and knowledge-innovation capabilities, has sparked a revolution in learning, teaching, assessment, and access to information. In particular, the Large Language Models represented by ChatGPT, based on OpenAI’s state-of-the-art technology, have greatly enriched the experience of interactive learning and have extended the boundaries of personalized education through the supervision and reinforcement of learning.

In this context, researchers in the fields of digital technology and education are exploring the diverse potential of AI in education, teaching, and the workplace, while keeping an eye on the challenges that this emerging technology may pose. “Application of generative AI technology in the field of education and its impact” can be summarized into two areas: One is to explore the harnessing of AI in education from the perspective of technology application, including the use of AI to support learners, teachers, and educational administrators in carrying out related teaching activities. This includes generative AI technology, as an auxiliary tool, to provide diversified contents and forms for teaching, such as enhancing personalized learning models, answering questions with virtual characters, and enriching the experience of teaching scenarios.

The other main elements in this front aim to explore the enhancement of relevant literacy from a human perspective – that is, whether students and teachers are prepared for the possible impact of AI technology on education. Some scholars have analyzed the deep-seated problems confronting the improvement of AI literacy, including academic plagiarism, teaching ethics, human rights, personalization, techno-solutionism, and colonialism.

“Application of generative AI technology in the field of education and its impact” is a research area full of potential as well as challenges. While AI technology is a powerful tool with tremendous potential for application in teaching, learning, management, and evaluation, there is no denying that certain limitations and challenges regarding its impact on ethics, academic misconduct, privacy, and other aspects, will require vigorous research attention and proactive measures before being resolved.

13

APPENDIX

RESEARCH FRONTS: IN SEARCH OF THE STRUCTURE OF SCIENCE

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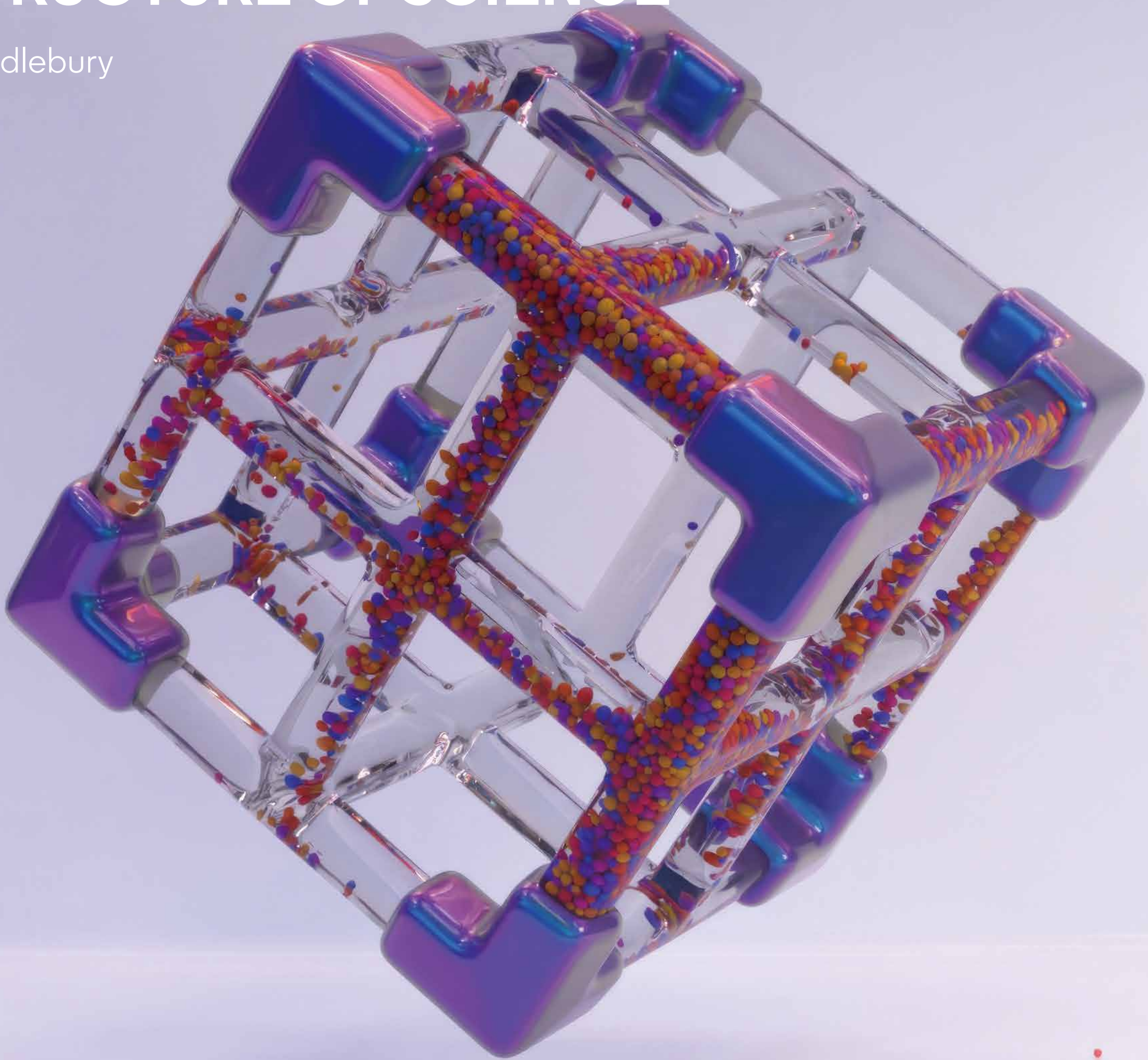

When Eugene Garfield introduced the concept of a citation index for the sciences in 1955, he emphasized its several advantages over traditional subject indexing.[1] Since a citation index records the references in each article indexed, a search can proceed from a known work of interest to more recently published items that cited that work. Moreover, a search in a citation index, either forward in time or backward through cited references, is both highly efficient and productive because it relies upon the informed judgments of researchers themselves, reflected in the references appended to their papers, rather than the choices of indexing terms by cataloguers who are less familiar with the content of each publication than are the authors. Garfield called these authors "an army of indexers" and his invention "an association-of-ideas index". He recognized citations as emblematic of specific topics, concepts, and methods: "the citation is a precise, unambiguous representation of a subject that requires no interpretation and is immune to changes in terminology."[2] In addition, a citation index is inherently cross-disciplinary and breaks through limitations imposed by source coverage. The connections represented by citations are not confined to one field or several – they naturally roam throughout the entire landscape of research. That is a particular strength of a citation index for science since interdisciplinary territory is well recognized as fertile ground for discovery. An early supporter of Garfield's idea, Nobel laureate Joshua Lederberg, saw this specific benefit of a citation index in his own field of genetics, which interacted with biochemistry, statistics, agriculture, and medicine. Although it took many years before the Science Citation Index (now the Web of Science) was fully accepted by librarians and the researcher community, the power of the idea and the utility of its implementation could not be denied. This year marks the 58th anniversary of the Science Citation Index, which first became commercially available in 1964. [3]

While the intended and primary use of the Science Citation Index was for information retrieval, Garfield knew almost from the start that his data could be exploited for the analysis of scientific research itself. First, he recognized that citation frequency was a method for identifying significant papers— ones with "impact"— and that such papers could be associated with specific specialties. Beyond this, he understood that there was a meaningful, if complex, structure represented in this vast database of papers and their associations through citations. In "Citation indexes for sociological and historical research," published in 1963, he stated that citation indexing provided an objective method for defining a field of inquiry.[4] That assertion rested on the same logical foundation that made information retrieval in a citation index effective: citations revealed the expert decisions and self-organizing behavior of researchers, their intellectual as well as their social associations. In 1964, with colleagues Irving H. Sher and Richard J. Torpie, Garfield produced his first historiograph, a linear mapping through time of influences and dependencies, illustrated by citation links, concerning the discovery of DNA and its structure. [5] Citation data, Garfield saw, provided some of the best material available for building out a picture of the structure of scientific research as it really was, even for sketching its terrain. Aside from making historiographs of specific sets of papers, however, a comprehensive map of science could not yet be charted.

Garfield was not alone in his vision. During the same era, the physicist and historian of science, Derek J. de Solla Price, was exploring the characteristic features and structures of the scientific research enterprise. The Yale University professor used the measuring tools of science on scientific activity, and he demonstrated in two influential books, of 1961 and 1963, how science had grown exponentially since the late 17th century, both in terms of number of researchers and publications.[6, 7] There was hardly a statistic about the activity of scientific research that his restless mind was not eager to obtain, interrogate, and play with. Price and Garfield became acquainted at this time, and Price, the son of a tailor, was soon receiving data, as he said, "from the cutting- room floor of ISI's computer room." [8] In 1965, Price published

"Networks of scientific papers," which used citation data to describe the nature of what he termed "the scientific research front." [9] Previously, he had used the term "research front" in a generic way, meaning the leading edge of research and including the most knowledgeable scientists working at the coalface. But in this paper, and using the short-lived field of research on N-rays as his example, he described the research front more specifically in terms of its density of publications and time dynamics as revealed by a network of papers arrayed chronologically and their inter-citation patterns. Price observed that a research front builds upon recently published work and that it displays a tight network of relationships.

"The total research front of science has never been a single row of knitting. It is, instead, divided by dropped stitches into quite small segments and strips. Such strips represent objectively defined subjects whose description may vary materially from year to year but which remain otherwise an intellectual whole. If one would work out the nature of such strips, it might lead to a method for delineating the topography of current scientific literature. With such a topography established, one could perhaps indicate the overlap and relative importance of journals and, indeed, of countries, authors, or individual papers by the place they occupied within the map, and by their degree of strategic centralness within a given strip."[10]

The year is 1972. Enter Henry Small, a young historian of science previously working at the American Institute of Physics in New York City who now joined the Institute for Scientific Information in Philadelphia hoping to make use of the Science Citation Index data and its wealth of title and key words. After his arrival, Small quickly changed allegiance from words to citations for the same reasons that had captivated and motivated Garfield and Price: their power and potential. In 1973, Small published a paper that was as groundbreaking in its own way as Garfield's 1955 paper introducing citation indexing for science. This paper, "Cocitation in the scientific literature: a new measure of relationship between two documents," introduced a new era in describing the specialty structure of science.[11] Small measured the similarity of two documents in terms of the number of times they were cited together, in other words their co-citation frequency. He illustrated his method of analysis with an example from recent papers in the literature of particle physics. Having found that such co-citation patterns indicated "the notion of subject similarity" and "the association or co-occurrence of ideas," he suggested that frequently cited papers, reflecting key concepts, methods, or experiments, could be used as a starting point for a co-citation analysis as an objective way to reveal the social and intellectual, or the socio-cognitive, structure of a specialty area. Like Price's research fronts, consisting of a relatively small group of recent papers tightly knit together, so too Small found co-citation analysis pointed to the specialty as the natural organizational unit of research, rather than traditionally defined and larger fields. Small also saw the potential for co-citation analysis to make, by analogy, movies and not merely snapshots. "The pattern of linkages among key papers establishes a structure or map for the specialty which may then be observed to change through time," he stated. "Through the study of these changing structures, co-citation provides a tool for monitoring the development of scientific fields, and for assessing the degree of interrelationship among specialties."

It should be noted that the Russian information scientist Irena V. Marshakova-Shaikevich also introduced the idea of co-citation analysis in 1973.[12] Since neither Small nor Marshakova-Shaikevich knew of each other's work, this was an instance of simultaneous and independent discovery. The sociologist of science Robert K. Merton designated the phenomenon "multiple discovery" and demonstrated that it is more common in the history of science than most recognize. [13,14] Both Small and Marshakova-Shaikevich contrasted co-citation with bibliographic coupling, which had been described by Myer Kessler in 1963. [15] Bibliographic coupling measures subject similarity between documents based on the frequency of shared cited references: if two works often cite the same literature, there is a probability they are related in their subject content. Co-citation analysis inverts this idea: instead of the similarity relation being established by what the publications cited, co-citation brings publications together by what cites them. With bibliographic coupling, the similarity relationships are static because their cited references are fixed, whereas similarity between documents determined by co-citation can change as new citing papers are published. Small has noted that he preferred co-citation to bibliographic coupling because he "sought a measure that reflected scientists' active and changing perceptions."[16]

The next year, 1974, Small and Belver C. Griffith of Drexel University in Philadelphia published a pair of landmark articles that laid the foundations for defining specialties using co-citation analysis and mapping them according to their similarity.[17,18] Although there have since been significant adjustments to the methodology used by Small and Griffith, the general approach and underlying principles remain the same. A selection is made of highly cited papers as the seeds for a co-citation analysis. The restriction to a small number of publications is justified because it is assumed that the citation histories of these publications mark them as influential and likely representative of key concepts in specific specialties, or research fronts. (The characteristic hyperbolic distribution of papers by citation frequency also suggests that this selection will be robust and representative.) Once these highly cited papers are harvested, they are analyzed for co-citation occurrence, and, of course, there are many zero matches. The co-cited pairs that are found are then connected to others through single-link clustering, meaning only one co-citation link is needed to bring a co-cited pair in association with another co-cited pair (the co-cited pair A and B is linked to the co-cited pair C and D because B and C are also co-cited). By raising or lowering a measure of co-citation strength for pairs of co-cited papers, it is possible to obtain clusters, or groupings, of various sizes. The lower the threshold, the more papers group together in large sets and setting the threshold too low can result in considerable chaining. Setting a higher threshold produces discrete specialty areas, but if the similarity threshold is set too high, there is too much disaggregation and many "isolates" form. The method of measuring co-citation similarity and the threshold of co-citation strength employed in creating research fronts has varied over the years. Today, we use cosine similarity, calculated as the co-citation frequency count divided by the square root of the product of the citation counts for the two papers. The minimum threshold for co-citation strength is a cosine similarity measure of .1, but this can be raised incrementally to break apart large clusters if the front exceeds a maximum number of core papers, which is set at 50. Trial and error has shown this procedure yields consistently meaningful research fronts.

To summarize, a Research Front consists of a group of highly cited papers that have been co-cited above a set threshold of similarity strength and their associated citing papers. In fact, the Research Front should be understood as both the co-cited core papers, representing a foundation for the specialty, and the citing papers that represent the more recent work and the leading edge of the Research Front. The name of the Research Front can be derived from a summarization of the titles of the core papers or the citing papers. The naming of Research Fronts in Essential Science Indicators relies on the titles of core papers. In other cases, the citing papers have been used: just as it is the citing authors who determine in their co-citations the pairing of important papers, it is also the citing authors who confer meaning on the content of the resulting Research Front. Naming Research Fronts is not a wholly algorithmic process, however. A careful, manual review of the cited or citing papers sharpens accuracy in naming a Research Front.

In the second of their two papers in 1974, [19] Small and Griffith showed that individual research fronts could be measured for their similarity with one another. Since co- citation defined core papers forming the nucleus of a specialty based on their similarity, co-citation could also define research fronts with close relationships to others. In their mapping of research fronts, Small and Griffith used multidimensional scaling and plotted similarity as proximity in two dimensions.

Price hailed the work of Small and Griffith, remarking that while co-citation analyses of the scientific literature into clusters that map on a two dimensional plane "may seem a rather abstruse finding," it was "revolutionary in its implications." He asserted: "The finding suggests that there is some type of natural order in science crying out to be recognized and diagnosed. Our method of indexing papers by descriptors or other terms is almost certainly at variance with this natural order. If we can successfully define the natural order, we will have created a sort of giant atlas of the corpus of scientific papers that can be maintained in real time for classifying and monitoring developments as they occur."[20] Garfield remarked that "the work by Small and Griffith was the last theoretical rivet needed to get our flying machine off the ground."[21] Garfield, ever the man of action, transformed the basic research findings into an information product offering benefits of both retrieval and analysis. The flying machine took off in 1981 as the ISI Atlas of Science: Biochemistry and Molecular Biology, 1978/80. [22] This book presented 102 research fronts, each including a map of the core papers and their relationships laid out by multidimensional scaling. A list of the core papers was provided with their citation counts, as well as a list of key citing documents, including a relevance weight for each that was the number of core documents cited. A short review, written by an expert in the specialty, accompanied these data. Finally, a large, foldout map showed all 102 research fronts plotted according to their similarities. It was a bold, cutting edge effort and a real gamble in the marketplace, but of a type wholly characteristic of Garfield.

The ISI Atlas of Science in its successive forms— another in book format and then a series of review journals [23,24] —did not survive beyond the 1980s, owing to business decisions at the time in which other products and pursuits held greater priority. But Garfield and Small both continued their research and experiments in science mapping over the decade and thereafter. In two papers published in 1985, Small introduced an important modification to his method for defining research fronts: fractional co-citation clustering. [25] By counting citation frequency fractionally, based on the length of the reference list in the citing papers, he was able to adjust for differences in the average rate of citation among fields and therefore remove the bias that whole counting gave to biomedical and other "high citing" fields. As a consequence, mathematics, for example, emerged more strongly, having been underrepresented by integer counting. He also showed that research fronts could be clustered for similarity at levels higher than groupings of individual fronts. [26] The same year, he and Garfield summarized these advances in "The geography of science: disciplinary and national mappings," which included a global map of science based on a combination of data in the Science Citation Index and the Social Sciences Citation Index, as well as lower level maps that were nested below the areas depicted on the global map. [27] "The reasons for the links between the macro-clusters are as important as their specific contents," the authors noted. "These links are the threads which hold the fabric of science together."

In the following years, Garfield focused on the development of historiographs and, with the assistance of Alexander I. Pudovkin and Vladimir S. Istomin, introduced the software tool HistCite. Not only does the HistCite program automatically generate chronological drawings of the citation relationships of a set of papers, thereby offering in thumbnail a progression of antecedent and descendant papers on a particular research topic, it also identifies related papers that may not have been considered in the original search and extraction. It is, therefore, also a tool for information retrieval and not only for historical analysis and science mapping. [28, 29] Small continued to refine his co-citation clustering methods and to analyze in detail and in context the cognitive connections found between fronts in the specialty maps. [30, 31] A persistent interest was the unity of the sciences. To demonstrate this unity, Small showed how one could identify strong co- citation relationships leading from one topic to another and travel along these pathways across disciplinary boundaries, even from economics to astrophysics.[32, 33]

In this, he shared the perspective of E. O. Wilson, expressed in the 1998 book Consilience: The Unity of Knowledge. [34] Early in the 1990s, Small developed SCI- MAP, a PC based system for interactively mapping the literature. [35] Later in the decade, he introduced Research Front data into the new database Essential Science Indicators (ESI), intended mainly for research performance analysis. The Research Fronts presented in ESI had the advantage of being updated every two months, along with the rest of the data and rankings in this product. It was at this time, too, that Small became interested in virtual reality software for its ability to create immersive, three-dimensional visualizations and to handle large datasets in real time. [36, 37] For example, in the late 1990s, Small played a leading role in a project to visualize and explore the scientific literature through co-citation analysis that was undertaken with Sandia National Laboratories using its virtual reality software tool called VxInsight. [38,39] This effort, with farsighted support of Sandia's senior research manager Charles E. Meyers, was an important step forward in exploiting rapidly developing technology that provided detailed and dynamic views of the literature as a geographic space with, for example, dense and prominent features depicted as mountains. Zooming into and out of the landscape allowed the user to travel from the specific to the general and back. Answers to queries made against the underlying data could be highlighted for visual understanding.

In fact, this moment—the late 1990s—was a turning point for science mapping, after which interest in and research about defining specialties and visualizing their relationships exploded. There are now a dozen academic centers across the globe focusing on science mapping, using a wide variety of techniques and tools. Developments over the last decade are summarized and illustrated in Indiana University professor Katy Borner's 2010 book, which carries a familiar-sounding title: Atlas of Science – Visualizing What We Know.[40]

The long interval between the advent of co-citation clustering for science mapping and the blossoming of the field, a period of about 25 years, is curiously about the same time it took from the introduction of citation indexing for science to the commercial success of the Science Citation Index. In retrospect, both were clearly ideas ahead of their time. While the adoption of the Science Citation Index faced ingrained perceptions and practice in the library world (and by extension among researchers whose patterns of information seeking were traditional), delayed enthusiasm for science mapping— a wholly new domain and activity—can probably be attributed to a lack of access to the amount of data required for the work as well as technological limitations that were not overcome until computing storage, speed, and software advanced substantially in the 1990s. Data are now more available and in larger quantity than in the past and personal computers and software adequate to the task. Today, the use of the Web of Science for information retrieval and research analysis and the use of Research Front data for mapping and analyzing scientific activity have found not only their audiences but also their advocates.

What Garfield and Small planted many seasons ago has firmly taken root and is growing with vigor in many directions. A great life, according to one definition, is "a thought conceived in youth and realized in later life." This adage applies to both men. Clarivate is committed to continuing and advancing the pioneering contributions of these two legends of information science.

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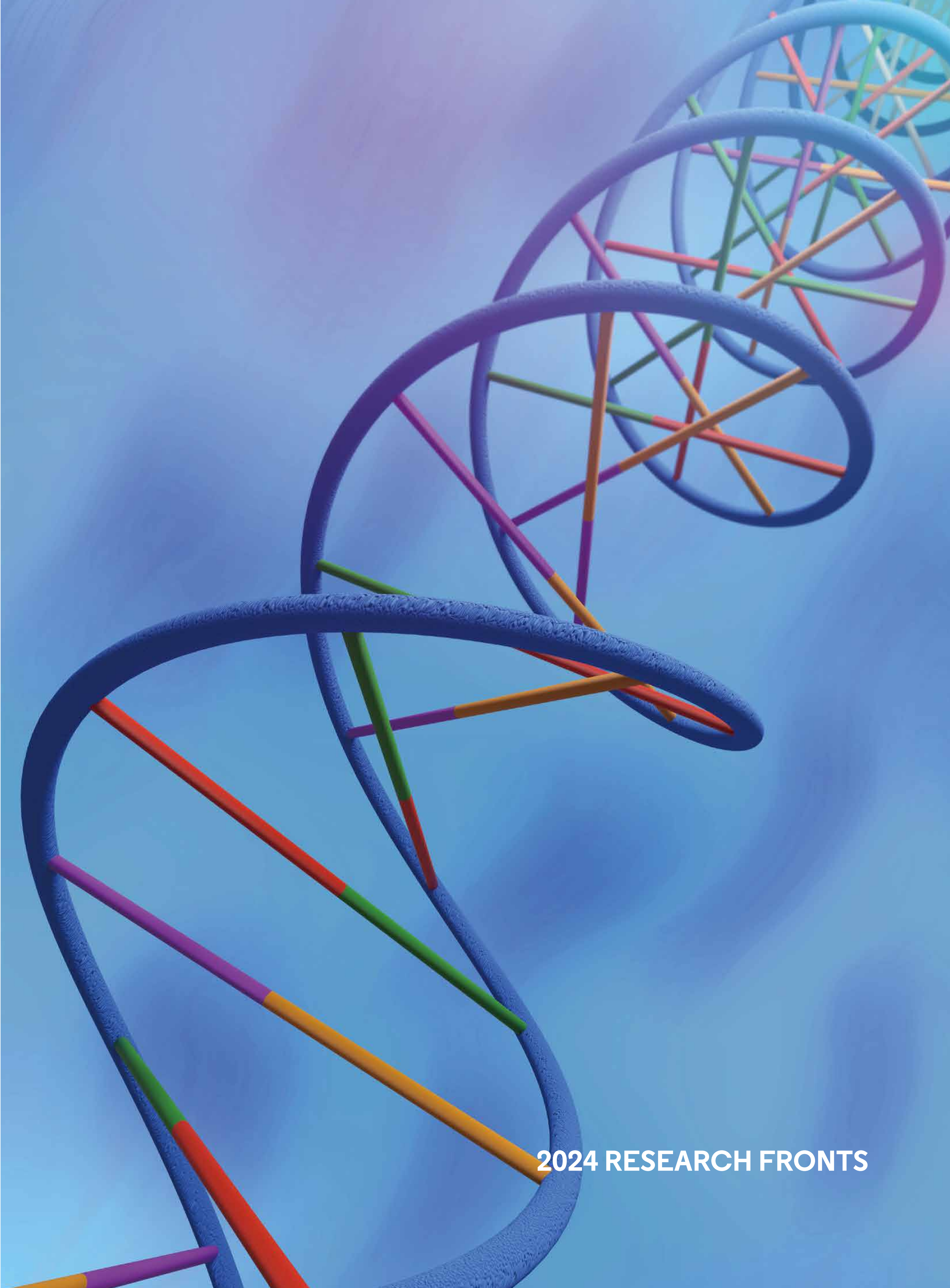
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About Institutes of Science and Development, Chinese Academy of Sciences

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