2025 RESEARCH FRONTS

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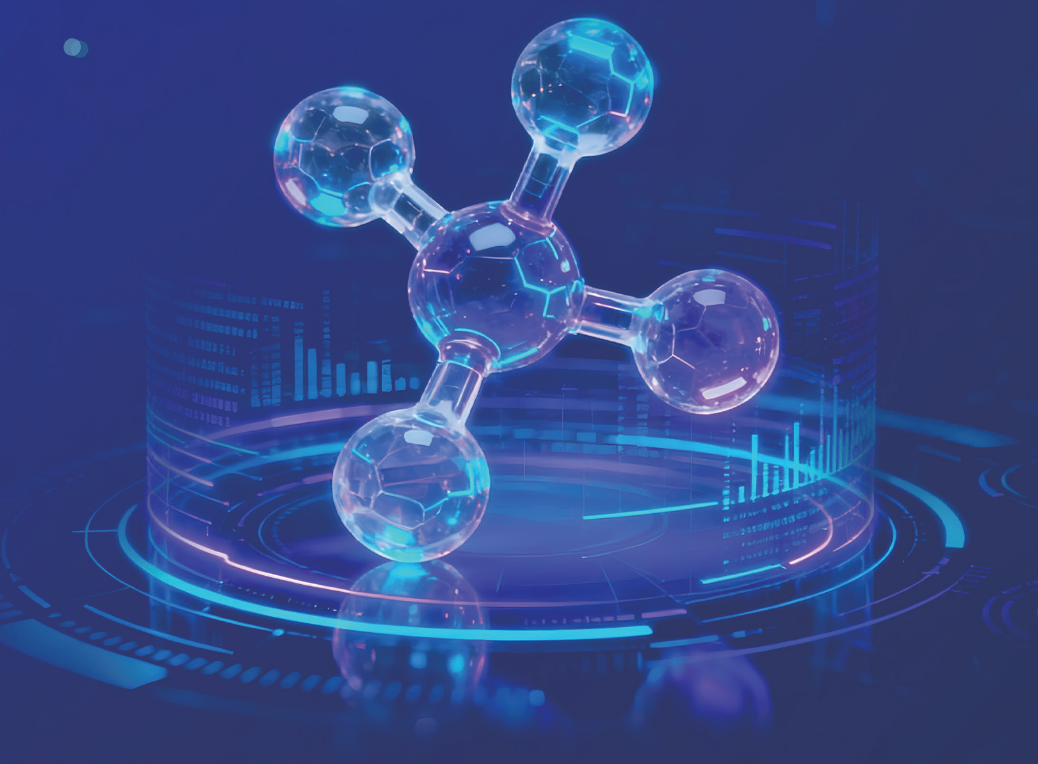

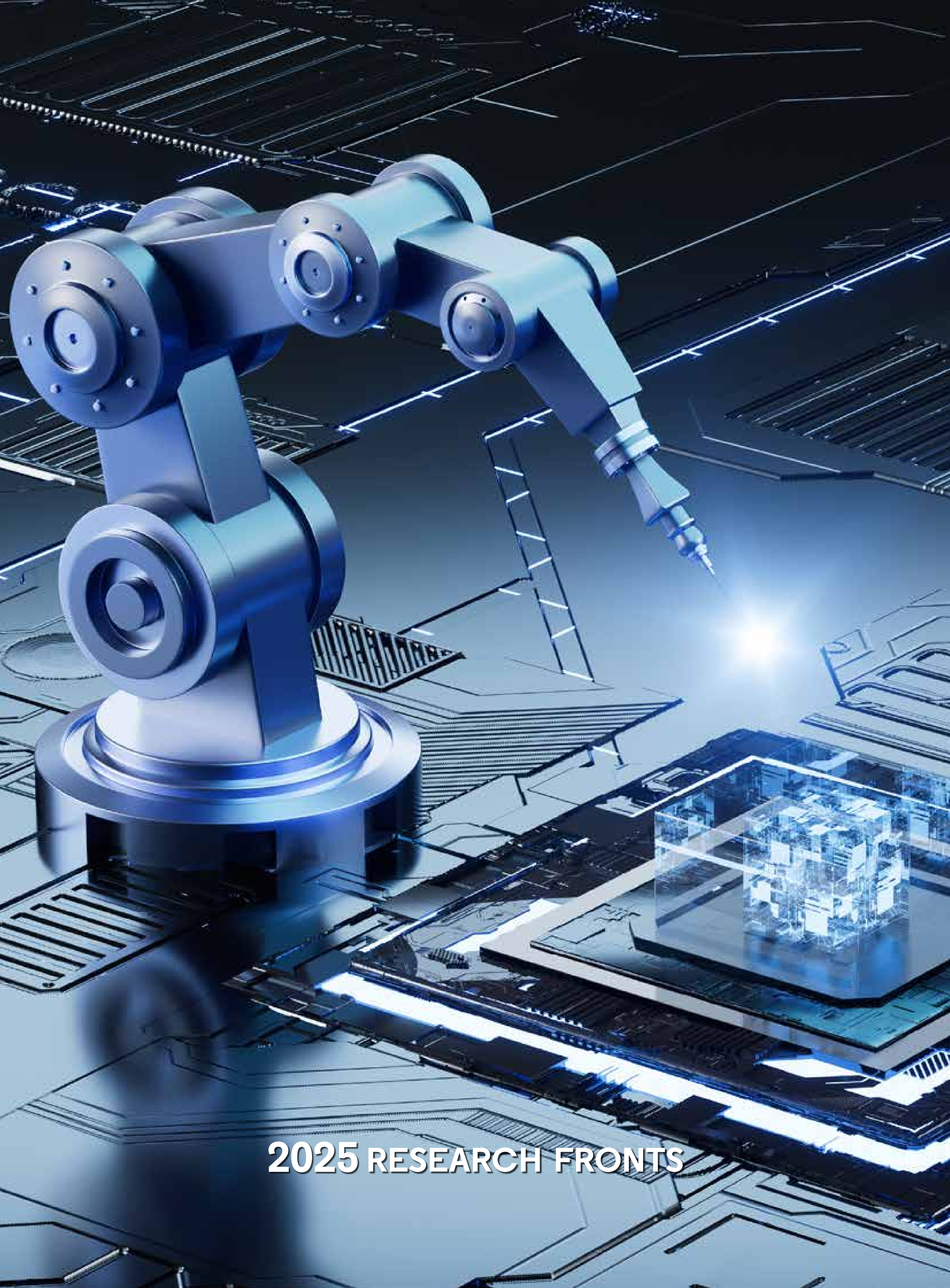
2025 RESEARCH FRONTS

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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 2024, 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, Research Fronts 2025 continues to be based on co-citation analysis in the field of bibliometrics. Using 13,830 Research Fronts from Clarivate's Essential Science Indicators™ (ESI) database, it identifies 107 hot Research Fronts and 18 emerging Research Fronts (including front clusters). Starting from 2025, the Research Fronts or front clusters selected in the report are collectively referred to as "Research Fronts." These fronts span 11 broad areas in the natural and social sciences. Additionally, based on Emerging Topics from the Research Horizon Navigator™ (RHN) database, three more hot fronts were selected, bringing the total to 110 hot fronts and 18 emerging fronts.

2. METHODOLOGY

The study was conducted in two parts. The process of selecting and naming 128 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 128 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 2025 update, the Research Fronts mainly drew on ESI data from 2019-2024, which were obtained in March 2025.

2.1 RESEARCH FRONTS SELECTION AND NAMING

The "2025 Research Fronts" report highlights 128 Research Fronts —110 hot fronts and 18 emerging fronts — spanning 11 broad areas* in the natural and social sciences. Drawing on Research Fronts from 20 disciplines in the ESI database and Emerging Topics from the RHN database, these were integrated into 11 broadly defined, highly aggregated research areas. Within this framework, the report identifies fronts characterized by strong research activity and rapid advancement.

The specific methodology used for identifying the 128 Research Fronts is described as follows.

2.1.1 SELECTING THE HOT RESEARCH FRONTS

This year, three 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 2025.

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.

Method 3: Similar to Method 1, Emerging Topics from the RHN database were first ranked by the citation network density between core papers and co-citing papers (i.e. citing papers that cite at least two core papers). The top 10% of Emerging Topics with the highest citation impact were then selected. These topics were subsequently re-ranked based on the average publication year of their core papers to identify the most recent, or "youngest"

* 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".

Emerging Topics. Finally, strategic information professionals with domain expertise reviewed, refined, and consolidated the selected topics.

By combining the three methods mentioned above, a total of 110 hot Research Fronts were selected, with 10 in each of the 11 broader areas. 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. 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).

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 in 20 ESI fields whose core papers dated, on average, to the second half of 2023 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 final selection of emerging Research Fronts and grouped them into 11 broader fields. Eighteen fronts were selected as emerging fronts for the 11 broader areas and their earliest mean publication year is 2023.6. Because the selection was not limited to any research area, the 18 fronts are distributed unevenly in the 11 fields. For example, in 2025 there is no emerging Research Front in "Mathematics", while there are four emerging Research Fronts in "Biological sciences".

Based on the above two processes, the report presents the Top 10 hot fronts in each of the 11 broad areas (110 fronts in total) and 18 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 128 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 128 Research Fronts provided by Clarivate, information professionals at the Institute of Strategic Information, conducted a detailed analysis and interpretation to highlight 31 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 2024 and the earliest citing paper was published in 2020, 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 2025*, 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, nine key emerging Research Fronts (including eight emerging Research Fronts and one front cluster consisting of four emerging fronts) were selected from the emerging Research Fronts. Thus, we interpret in detail the selected 31 key Research Fronts from the 128 Research

Fronts.

2.2.2 ANALYSIS AND INTEPRETATION OF KEY RESEARCH FRONTS

Based on the data of the selected 128 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 31 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.

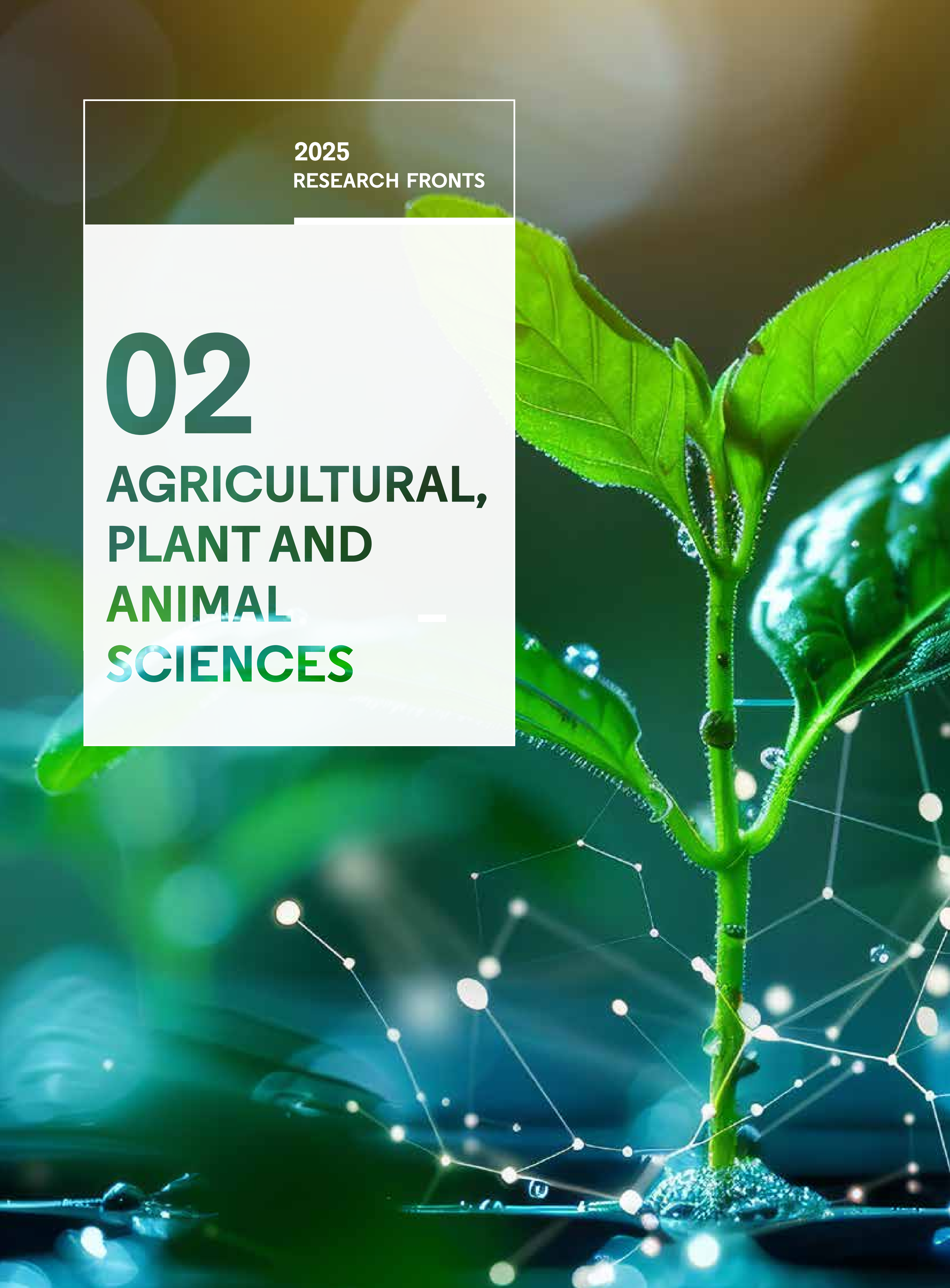
The first table under each discipline section lists the 10 top ranked Research Fronts for each of the 11 broad areas, as well as the number of core papers, total citations, and the average publication year of the core papers of each Research Front. A bubble diagram shows the age distribution of the citing 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 six subfields: animal health and public health; plant stress resistance; plant molecular mechanisms; plant evolutionary biology and genetic resource mining; plant disease prevention and control; and food science and engineering (Table 1). The subfield of animal health and public health covers research on intercontinental spread and cross-species infection of highly pathogenic avian influenza H5N1. The specialty area on plant stress resistance focuses on the defense mechanisms of plants under abiotic stress, as well as the development of technologies to alleviate salinity stress in plants. Meanwhile, research on plant molecular mechanisms concentrates on the temperature-sensing mechanisms of plants, and the plant epigenetic transcriptional regulation of N6-methyladenosine modification.

The subfield of plant evolutionary biology and genetic resource mining concerns the origin and early evolution of terrestrial plants, and exploring resistance genes from wild relatives of wheat. The specialty area on plant disease prevention and control emphasizes the application of new technologies such as deep learning and biosynthesis of metal nanoparticles in disease detection and control. Finally, food science and engineering focuses on the integration of food nutrition and engineering technology, with a primary emphasis on the development of dysphagia diet – the modification of foods for individuals with swallowing difficulties.

Over the past 12 years of these Research Fronts surveys, several characteristics have revealed themselves. First, the subfield of animal health and public health has attracted widespread attention since the COVID-19 pandemic. In both 2021 and 2022, one front from this area was selected among the Top 10 hot Research Fronts, namely “Epidemiological and virological research and prevention and control of African swine fever” in 2021, and “Infection and transmission of SARS-COV-2 in domestic animals” in 2022. This year, another new front, “Intercontinental spread and cross-species infection of highly pathogenic avian influenza H5N1”, has also made the list.

Marking another ongoing trend, N6-methyladenosine modification has become a research hotspot in epigenetic transcriptional regulation and has appeared in the Top 10 for two consecutive years, last year and this year. In a third continuing theme, plant disease detection powered by artificial intelligence (AI) has become a new research hotspot. Following the selection of “Application of deep transfer learning in crop classification and disease detection” as an emerging front in 2024, this year “Plant diseases and pests detection based on deep learning” earned a place among the Top 10 hot Research Fronts. And one more notable trend: The integration of food nutrition and engineering technology has deepened in scope. In 2022, “3D food printing” was selected for the Top 10 hot fronts, and this year “3D printing of dysphagia diet” earned that distinction.

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

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Intercontinental spread and cross-species infection of highly pathogenic avian influenza H5N1	46	2354	2023.1
2	Physio-biochemical responses and antioxidant defense of plants under abiotic stress	17	1181	2022.3
3	Biosynthesis of metallic nanoparticles and their effect on controlling plant diseases and promoting plant growth	16	1526	2022.1
4	N6-detection, regulation, and functions of RNA methyladenosine modification in plants	22	1322	2022.1
5	The origin and early evolution of plants	20	2374	2022.0
6	Exploring resistance genes for wheat improvement from wild crop relatives	20	2244	2021.6
7	**Using plant growth-promoting bacteria to alleviate salinity stress in plants**	**19**	**1729**	**2021.5**
8	The temperature sensing mechanisms of Arabidopsis thaliana	11	1140	2021.5
9	**Plant diseases and pests detection based on deep learning**	**46**	**5951**	**2021.2**
10	3D printing of dysphagia diet	13	1656	2021.0

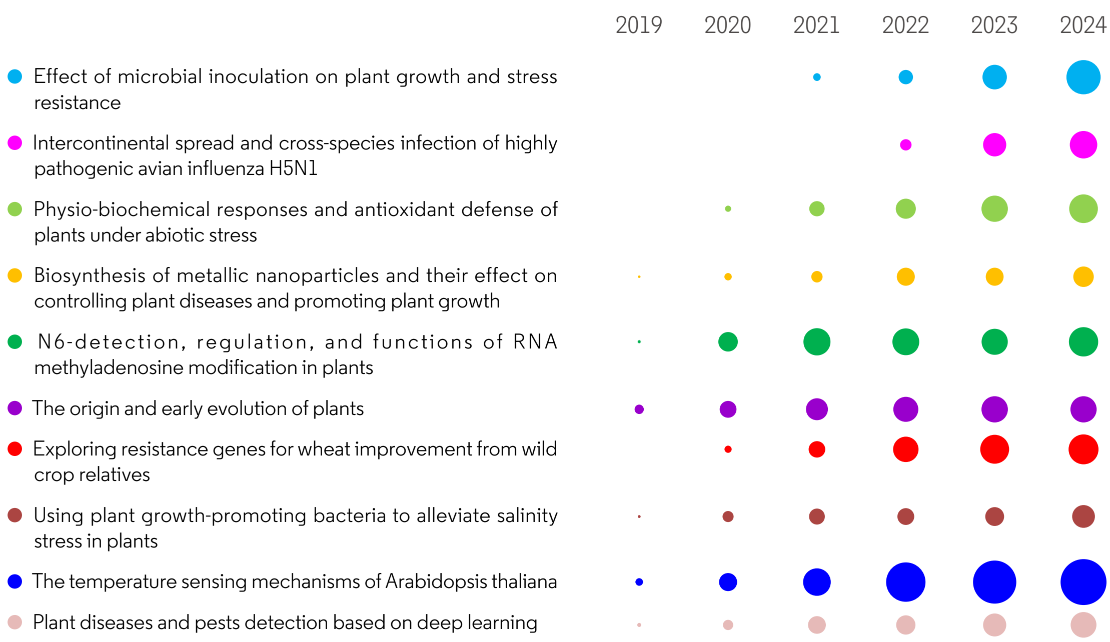


Figure 1: Citing papers for the Top 10 Research Fronts in agricultural, plant and animal sciences

1.2 KEY HOT RESEARCH FRONT – "Using plant growth-promoting bacteria to alleviate salinity stress in plants"

Salinity stress is one of the major abiotic stresses threatening sustainable crop production worldwide. The extent of areas affected by salinity is expected to cover about 50% of total agricultural land by 2050. Salinity stress produces various detrimental effects on plants' physiological, biochemical, and molecular features, subsequently reducing productivity. The use of plantgrowth-promoting rhizobia (PGPR) to alleviate salt stress in plants has become a multidisciplinary research hotspot. From the early 21st century onward, research on PGPR has evolved from initial observation of phenomena to current molecular mechanism analysis and microbial engineering applications, presenting three major development trends: 1) Research on mechanisms of actions continues to deepen; 2) The focus of strain mining has shifted from single strains to complex microbial communities; 3) Field trials and industrialization of microbial agents are continuously advancing.

In the future, models will be created by integrating AI and big data to predict the functional characteristics of PGPR strains or microbial communities under specific environmental conditions, enabling more precise agricultural applications. In summary, as a biological regulatory tool, PGPR has broad prospects in alleviating salt stress and increasing crop yield.

Nineteen core papers anchor this hot Research Front, focusing on the resource mining of new PGPR strains, analysis of mechanisms employed by PGPR, and evaluation of salt tolerance. The resource mining study involves isolating new salt-tolerant strains from maize rhizosphere soil and sand dune flora found on beaches. The mechanism analysis reveals that PGPR can alleviate salt stress by regulating such factors as plant hormone levels, nutrient acquisition, redox potential, ion homeostasis, photosynthetic capacity, secondary metabolites and molecular reactions, chlorophyll content, proline content, total soluble sugars, electrolyte leakage, and antioxidant enzyme activity. The evaluation of salt tolerance aims to delve into the effects of PGPR on salt tolerance, growth, and the development of crops such as peas, soybeans, corn, tomatoes, peanuts, mustard greens, rapeseed, and cotton.

Among the core papers, the most frequently cited research article was published in *Environmental and Experimental Botany* in 2020 by researchers at the University of Tehran in Iran and the University of Waterloo in Canda. This report has attracted 160 citations at this writing (Figure 2). Based on the study of the rhizosphere microbiome of halophilic plants, this article concludes that the microbiome plays a dominant role in the growth and development of salinity-sensitive plants under salt stress. Bacterial microbiome associated with the roots of halophytic plants exhibits multiple plant growth-promoting characteristics, such as the production of different phytohormones, dissolution of insoluble inorganic phosphates, siderophore production, molecular nitrogen fixation, and pathogen suppression.

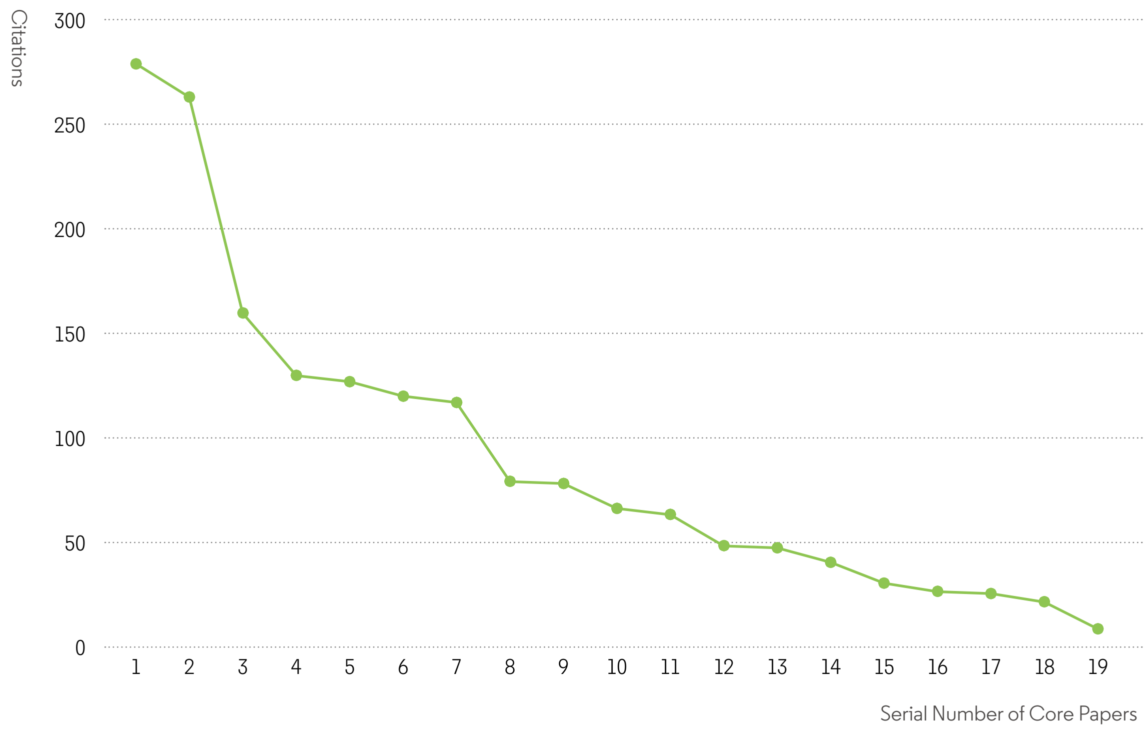
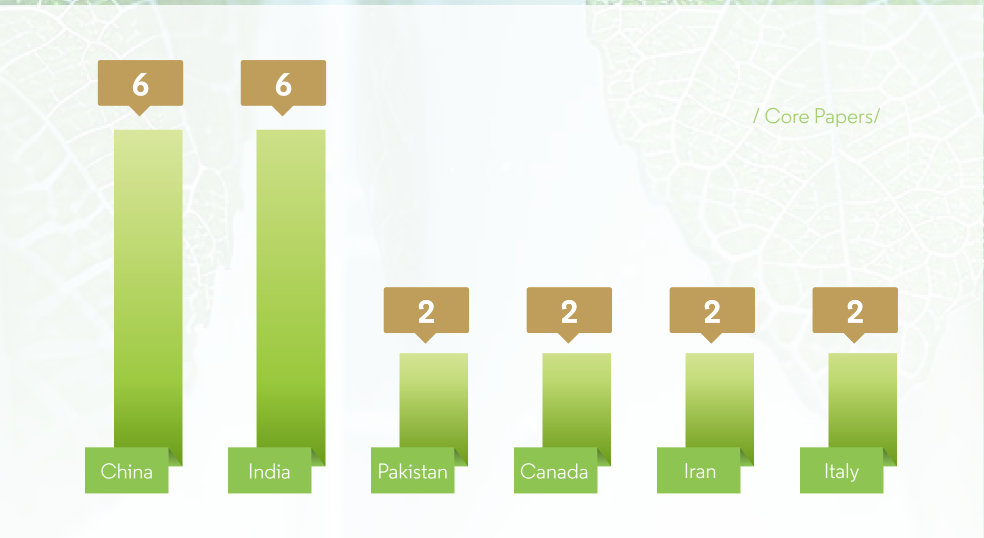


Figure 2: Citation frequency distribution curve of core papers in the Research Front "Using plant growth-promoting bacteria to alleviate salinity stress in plants"

Among the top countries and institutions producing core papers (Table 2), China and India contributed the most, with six papers apiece, accounting for approximately 32%. Pakistan, Canada, Iran, and Italy each contributed two papers. Among the prolific contributing institutions, the University of Waterloo in Canda, the University of Tehran in Iran, and the Babasaheb Bhimrao Ambedkar University in India each produced two papers.

Table 2: Top countries and institutions producing core papers in the Research Front "Using plant growth-promoting bacteria to alleviate salinity stress in plants"

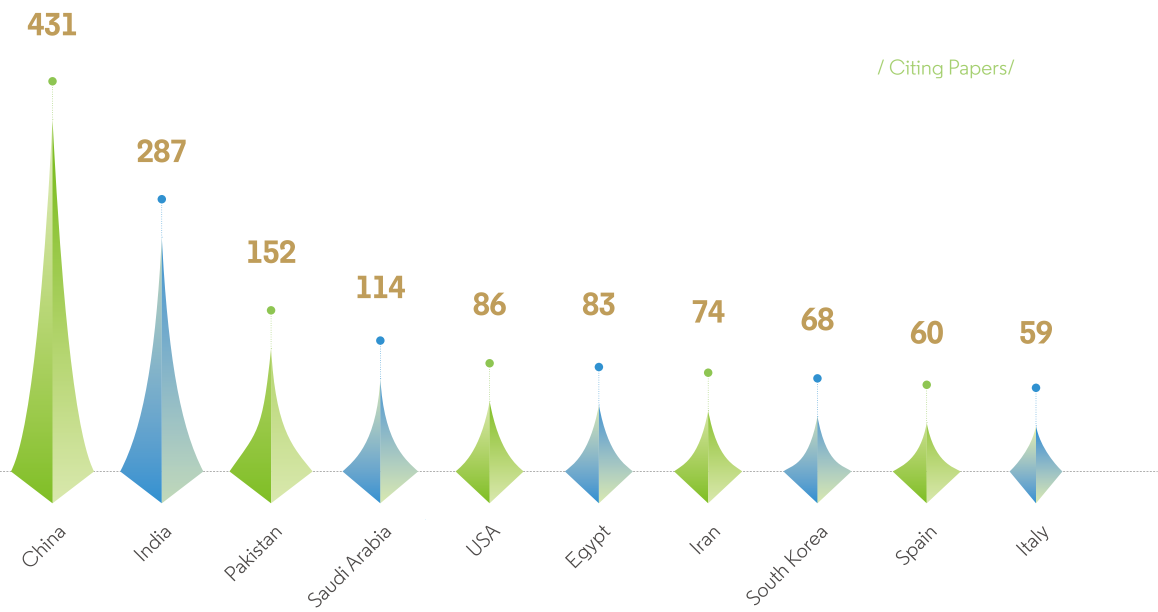
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	6	31.6%	1	University of Waterloo	Canada	2	10.5%
1	India	6	31.6%	1	University of Tehran	Iran	2	10.5%
3	Pakistan	2	10.5%	1	Babasaheb Bhimrao Ambedkar University	India	2	10.5%
3	Canada	2	10.5%					
3	Iran	2	10.5%					
3	Italy	2	10.5%					



In terms of citing papers (Table 3), China remains the top contributor with 431 reports, representing approximately 33% of the total, far ahead of other countries, demonstrating the nation's strong focus and ongoing research interest in this area. India ranks 2nd with 287 papers, accounting for 22% of the total. Pakistan and Saudi Arabia are actively following suit, forming the third tier in terms of citing-paper output. Among the top citing institutions, the King Saud University in Saudi Arabia has contributed 57 citing papers, ranking 1st, followed closely by the Chinese Academy of Sciences and Indian Council of Agricultural Research, with 50 citing papers each.

Table 3: Top countries and institutions producing citing papers in the Research Front "Using plant growth-promoting bacteria to alleviate salinity stress in plants"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	431	32.8%	1	King Saud University	Saudi Arabia	57	4.3%
2	India	287	21.8%	2	Chinese Academy of Sciences	China	50	3.8%
3	Pakistan	152	11.6%	2	Indian Council of Agricultural Research	India	50	3.8%
4	Saudi Arabia	114	8.7%	4	University of Agriculture Faisalabad	Pakistan	45	3.4%
5	USA	86	6.5%	5	Government College University Faisalabad	Pakistan	27	2.1%
6	Egypt	83	6.3%	6	Chinese Academy of Agricultural Sciences	China	24	1.8%
7	Iran	74	5.6%	7	Kyungpook National University	South Korea	23	1.7%
8	South Korea	68	5.2%	8	University of Tehran	Iran	22	1.7%
9	Spain	60	4.6%	9	Yeungnam University	South Korea	20	1.5%
10	Italy	59	4.5%	10	University of Waterloo	Canada	19	1.4%



1.3 KEY HOT RESEARCH FRONT – "Plant diseases and pests detection based on deep learning"

Plant diseases not only significantly reduce the quality and quantity of agricultural products but also have a major impact on food-production safety. Early detection is the basis for effective prevention and control of plant diseases, and those measures play a vital role in the management and decision-making of agricultural production. Traditional disease methods of diagnosis usually rely on human experts for visual inspection—a process that is time consuming, labor-intensive, and susceptible to subjective factors.

In recent years, the branch of AI known as deep learning has developed rapidly and provided new solutions for automated detection of plant diseases, making significant progress. Even researchers with limited expertise in plant protection and statistics can leverage deep learning techniques to automatically extract image features and provide classification of plant disease, eliminating the considerable work associated with traditional technology. These capabilities have led to the widespread application of deep learning technology in plant-disease identification, making it a research hotspot.

Forty-six core papers underlie this hot Research Front, focusing on deep learning methods based on convolutional neural networks, deep convolutional neural networks, and deep residual neural networks. These studies aim to construct models for recognizing plant leaf disease, whether identifying plant diseases from the entire leaf or individual lesions and spots. This research involves numerous crop species, including grain crops, fruits and vegetables such as rice, wheat, tomatoes, cucumbers, apples, citrus, bananas, grapes. The diseases in question afflict rice, including bacterial blight, false smut, brown leaf spot, blast and sheath blight; also wheat, including leaf blotch caused by Septoria tritici, brown spot, and stripe rust; in tomatoes, including gray spot, early blight, late blight, along with leaf mold; as well as black rot, black measles, and mite disease in grapes.

Among the core papers in this front, the most cited has attracted more than 400 citations at this writing (Figure

3). It was published in Computers and Electronics in Agriculture in 2019 by researchers at two Chinese institutions: the University of Science and Technology Beijing, and the Academy of Forest Inventory & Planning, National Forestry and Grassland Administration. This work focuses on fine-tuning and evaluating state-of-the-art deep convolutional neural network for image-based plant disease classification, along with conducting an empirical comparison of deep learning architecture, aiming to find fast and accurate models for plant disease identification.

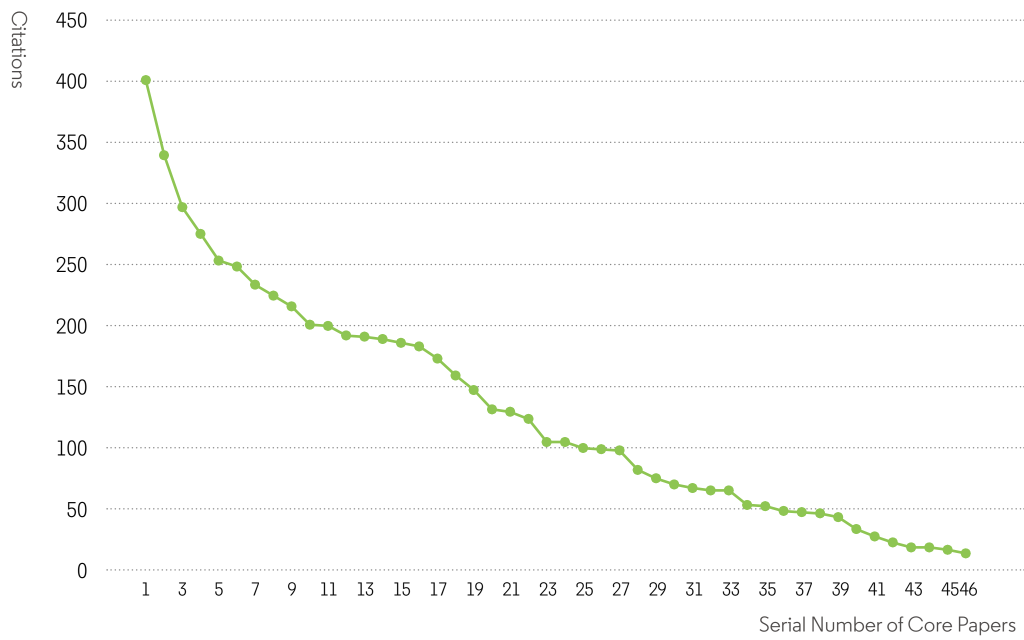
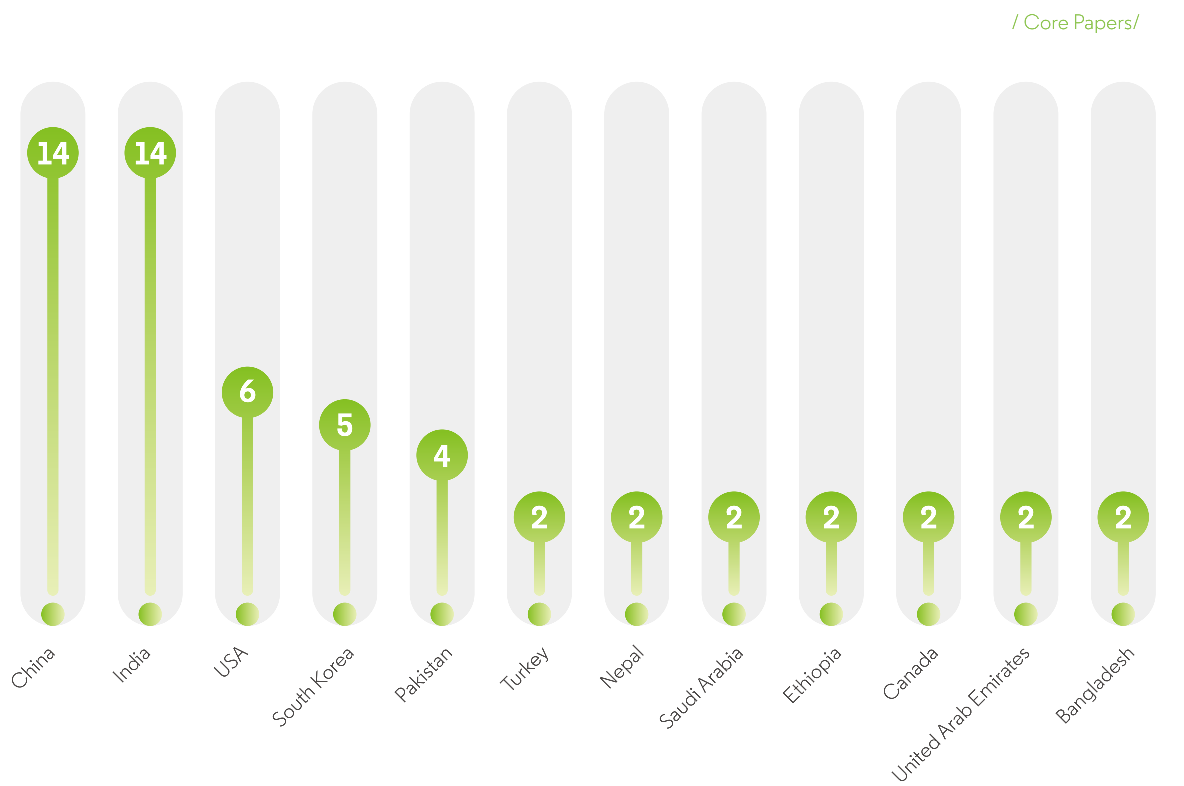


Figure 3: Citation frequency distribution curve of core papers in the Research Front "Plant diseases and pests detection based on deep learning"

Among the top countries and institutions producing core papers (Table 4), China and India field the highest contributions, tied for first place with 14 reports each, representing approximately 30% of the total. The USA and South Korea follow suit, contributing six and five papers, respectively. Among institutions, notable performers are Sejong University in South Korea, joined by China Agricultural University, and Weifang University of Science and Technology in China.

Table 4: Top countries and institutions producing core papers in the Research Front "Plant diseases and pests detection based on deep learning"

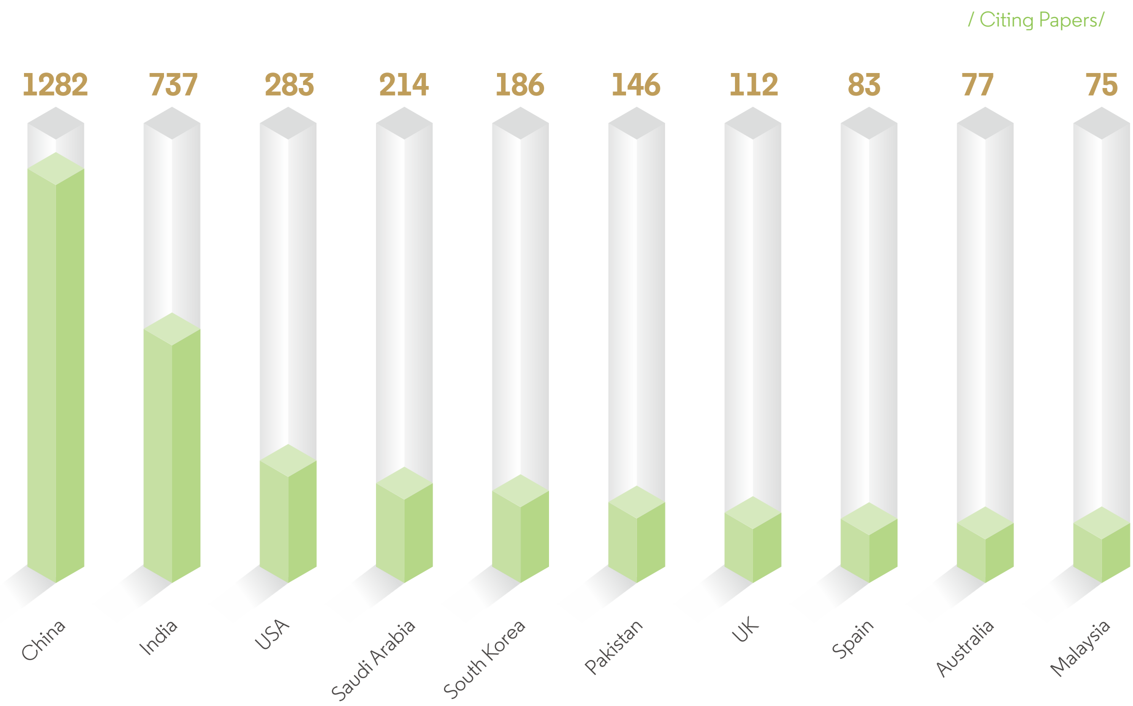
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	14	30.4%	1	Sejong University	South Korea	3	6.5%
1	India	14	30.4%	1	China Agricultural University	China	3	6.5%
3	USA	6	13.0%	1	Weifang University of Science and Technology	China	3	6.5%
4	South Korea	5	10.9%	4	Vellore Institute of Technology (VIT)	India	2	4.3%
5	Pakistan	4	8.7%	4	Zayed University	United Arab Emirates	2	4.3%
6	Turkey	2	4.3%	4	Northwest A&F University	China	2	4.3%
6	Nepal	2	4.3%					
6	Saudi Arabia	2	4.3%					
6	Ethiopia	2	4.3%					
6	Canada	2	4.3%					
6	United Arab Emirates	2	4.3%					
6	Bangladesh	2	4.3%					



In terms of countries and institutions that cite the core papers in this hot front (Table 5), China ranks 1st with more than 1,280 papers to date, accounting for almost 40%, while India ranks 2nd with nearly 740 papers, representing approximately 23%. This performance demonstrates these two nations' strong focus and sustained attention in this research area, registering far ahead of other countries. China ties for first place with India in the production of core papers, while, by the measure of citing papers, exceeding India by more than 540 follow-up reports. The USA ranks 3rd in citing paper output, consistent with its ranking in core-paper production. In terms of citing institutions, China-based entities demonstrate remarkable prominence, with six institutions in the Top10. Among them, China Agricultural University, the Chinese Academy of Agricultural Sciences, and the Chinese Academy of Sciences rank 1st, 2nd, and 3rd respectively. India has three institutions in the Top10, ranking 4th, 7th, and 9th.

Table 5: Top countries and institutions producing citing papers in the Research Front "Plant diseases and pests detection based on deep learning"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1282	39.5%	1	China Agricultural University	China	109	3.4%
2	India	737	22.7%	2	Chinese Academy of Agricultural Sciences	China	66	2.0%
3	USA	283	8.7%	3	Chinese Academy of Sciences	China	65	2.0%
4	Saudi Arabia	214	6.6%	4	Vellore Institute of Technology (VIT)	India	53	1.6%
5	South Korea	186	5.7%	5	South China Agricultural University	China	48	1.5%
6	Pakistan	146	4.5%	6	Northwest A&F University	China	44	1.4%
7	UK	112	3.5%	7	Indian Council of Agricultural Research	India	41	1.3%
8	Spain	83	2.6%	8	Zhejiang University	China	39	1.2%
9	Australia	77	2.4%	9	King Saud University	Saudi Arabia	38	1.2%
10	Malaysia	75	2.3%	9	SRM Institute of Science and Technology	India	38	1.2%



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, one emerging Research Front has been identified: "The application of anthocyanins in intelligent food packaging films" (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	The application of anthocyanins in intelligent food packaging films	10	169	2023.8

2.2 KEY EMERGING RESEARCH FRONT – "The application of anthocyanins in intelligent food packaging films"

Anthocyanins are natural pigments with various bioactivities that are beneficial to health and commonly used in food processing. In recent years, they have also become a research hotspot in the field of intelligent food packaging, a discipline that aims not only to enhance the functionality of packaging, but to provide better protection for food.

Intelligent packaging is a technology that can achieve advanced functions such as detection, sensing, recording, tracking, and communication. In turn, these elements can be used to support decision-making, extend shelf life, enhance food safety, improve food quality, provide food information, and raise alert of potential risks.

The structure and color of anthocyanins vary with environmental pH changes, so they are commonly used as pH indicators to monitor the freshness of food in intelligent packaging. In addition, due to their strong antibacterial and antioxidant properties, anthocyanins also play an important role in food packaging and storage. Meanwhile, environmental conditions such as temperature, humidity, gas, pressure, light, and chemical reactions can also cause changes in anthocyanins. Therefore, these pigments are expected to be used in the future as time-temperature indicators and gas indicators.

This emerging front comprises 10 core papers, focusing on the preparation of intelligent food-packaging films which utilize anthocyanins as indicators to monitor food freshness. Anthocyanins are mainly extracted from butterfly pea flower, Broussonetia papyrifera fruit, bilberry, Garcinia mangostana shell, and blueberry. The film-forming substrates used in preparing intelligent packaging films primarily include chitosan and gelatin composites, mica nanosheets, konjac glucomannan, carrageenan and gellan gum composites, sodium alginate-carrageenan polysaccharide matrix, natural polysaccharide chitosan, composites of carboxymethyl cellulose and corn starch, or composites of wheat gluten protein and apple pectin. Research on maintaining food freshness mainly focuses on beef, shrimp, and fish. The results show that these intelligent packaging films have great potential in monitoring food freshness and delaying spoilage.

2025
RESEARCH FRONTS

03

ECOLOGY AND ENVIRONMENTAL SCIENCES

1.HOT RESEARCH FRONT

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

The Top 10 hot Research Fronts 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-sciences subfield mainly focus on health toxicology research pertaining to emerging pollutants—including the treatment of pollutants—along with carbon-sequestration technologies. Research on aspects of emerging pollutants has been recurrent hot topic in environmental sciences. In particular, the theme of microplastics has remained highly popular for more than a decade, with related studies repeatedly selected as hot and emerging Research Fronts during 2015–2017 and 2020–2024.

As in the 2024 report, two hot fronts—”Detection and quantitative analysis of microplastics in human tissue” and “Environmental fate and ecotoxicity of tire wear particles”—were once again jointly selected as hot fronts in 2025. In addition, Research Fronts related to pollution control technologies include “Mechanism of single-atom catalysts activating peroxymonosulfate for highly selective degradation of pollutants” and “Research and application of nanofiltration membranes for efficient separation of lithium ions”. Of these, Research Fronts related to peroxymonosulfate degradation of pollutants have also been selected as hot fronts for multiple consecutive years. Meanwhile, carbon sequestration technologies for addressing climate change have been receiving heightened attention. In 2025, the related hot front is “Preparation of biomass derived porous activated carbon adsorbent and CO_2 capture performance”.

The hot Research Fronts in the ecological-science subfield mainly emphasize biodiversity research and protection. Genetic diversity is a crucial aspect of biodiversity and is essential for the stability and adaptability of ecosystems. In 2025, “The significance and application of genetic diversity in biodiversity conservation” emerged as a hot front.

Additionally, fronts related to research at the intersection of ecology and environmental sciences became further highlighted in 2025. These include the planetary boundaries theory, which addresses environmental and ecological concerns, with the hot front “Planetary boundaries transgression/breaches and earth system risk governance”; climate change-related fronts such as “Climate impacts of the global aviation and Pathways to Net-Zero Emissions”; and research on China’s carbon neutrality policies, including “Pathways for China to achieve Carbon Neutrality and low-carbon transition of the Energy System” and “Evaluation of the effectiveness of China’s Low-Carbon City pilot policies”.

In sum, the hot Research Fronts in the field of ecology and environmental sciences in 2025 are more focused on emerging pollutants, carbon neutrality, and macro-level ecological and environmental issues at the global or regional scale.

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	43	2958	2023.0
2	**Planetary boundaries transgression and Earth system risk governance**	**7**	**1954**	**2022.4**
3	Mechanism of single-atom catalysts activating peroxymonosulfate for highly selective degradation of pollutants	21	4427	2021.8
4	Pathways for China to achieve Carbon Neutrality and low-carbon transition of the Energy System	12	1933	2021.8
5	**Preparation of biomass derived porous activated carbon adsorbent and CO_2 capture performance**	**26**	**2916**	**2021.7**
6	Climate impacts of the global aviation and Pathways to Net-Zero Emissions	11	1563	2021.5
7	Research and application of nanofiltration membrane technology for efficient separation of lithium ions	38	6050	2021.4
8	Evaluation of the effectiveness of China's Low-Carbon City pilot policies	14	2627	2021.4
9	The significance and application of genetic diversity in biodiversity conservation	15	2138	2021.3
10	Detection and quantitative analysis of microplastics in human tissue	6	4862	2021.2

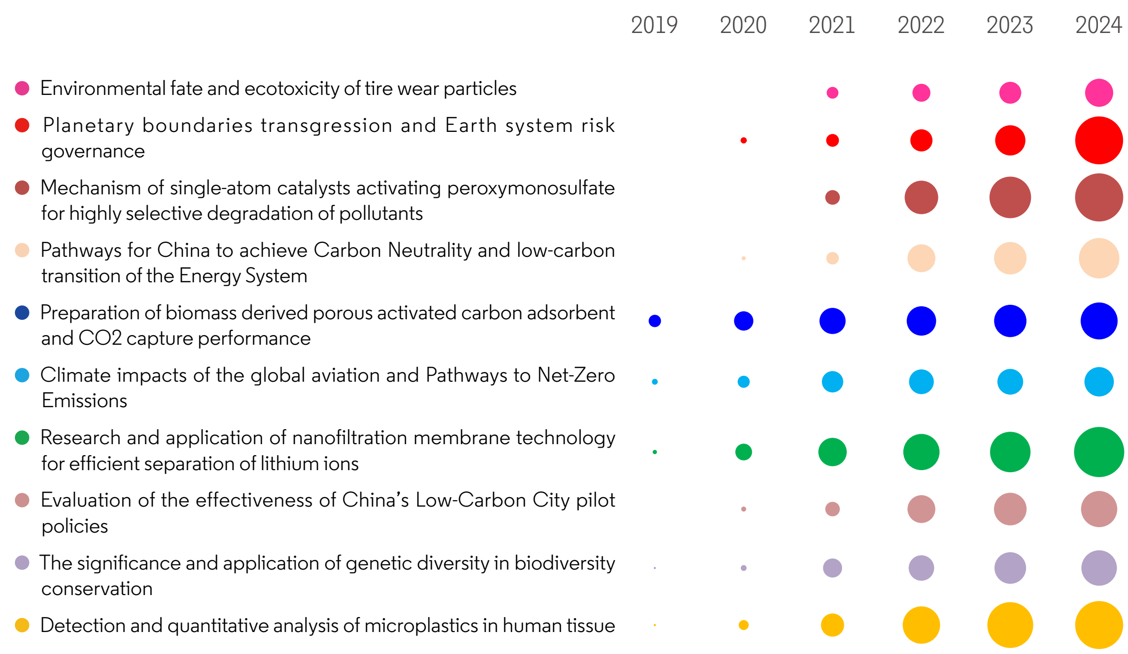


Figure 4: Citing papers for the Top 10 Research Fronts in ecology and environmental sciences

1.2 KEY HOT RESEARCH FRONT "Planetary boundaries transgression and Earth system risk governance"

Planetary boundaries, also known as Earth's limits or Earth boundaries, is a theoretical framework proposed in 2009 by a team of 28 leading scientists led by Johan Rockström from Stockholm University. This framework defines the limits within which humanity can safely operate without causing significant environmental disruption, establishing "a safe operating space" for the Earth system. Overall, this framework aims at ensuring that the reasonable scope or extent of human activities avoid causing severe anthropogenic environmental changes on a global scale. This approach reduces the risk of human activities exceeding the ecological thresholds of the Earth system, with the goal of maintaining the current environmental functions and life-support systems in a state similar to that of the past 10,000 years, thereby ensuring human survival.

Within these boundaries, humanity and future generations can continue to thrive, whereas exceeding those limits increases the risk of abrupt or irreversible environmental changes. The framework identifies nine key Earth system processes that regulate the stability and resilience of the planet and quantify thresholds for some of these processes. These nine key system processes include climate change, biogeochemical flows, freshwater change, land system change, biosphere integrity, novel entities, ocean acidification, atmospheric aerosol loading, and stratospheric ozone depletion.

Currently, all these processes are severely disrupted by human activities. Since its introduction, this theoretical framework has garnered widespread attention from the international scientific community and society, inspiring governmental strategies and policies at various levels. Concurrently, the framework is continuously updated in accordance with the latest scientific understanding.

The seven core papers in this hot Research Front primarily focus on the theoretical development and refinement of the planetary boundaries framework. They propose the addition of new control variables for planetary boundaries, such as green water and novel entities, while also calling for more robust scientific and policy tools to analyze the entire Earth system and guide political processes, and emphasizing the integration of equity considerations in scientifically defining planetary boundaries to reduce harm to human well-being. This framework holds the potential to steer humanity toward seizing critical opportunities for sustainable global development and inspiring the world to move toward a future that genuinely safeguards and strengthens the stability of the Earth system.

The most-cited core paper in this front comes from a team of 29 scientists led by Katherine Richardson from the University of Copenhagen, Denmark, with Johan Rockström, one of the founders of the planetary boundaries theoretical framework, as a co-author. This article was published in *Science Advances* in September 2023 and has already been cited more than 506 times. The study updates the status of the planetary boundaries, revealing that six of the nine boundaries have already exceededsafe operating limits. For example, ocean acidification is on the verge of being breached, regional aerosol loading has surpassed the boundary, and although stratospheric ozone levels have slightly recovered thanks to human efforts, all previously transgressed boundaries have worsened. These findings indicate that the Earth has now moved far beyond safe operating limits. The study emphasizes the need to examine the impact of human activities on the Earth system from a holistic perspective, to focus on the biosphere-geosphere interactions within the Earth system, and to recognize the critical importance of the land system change boundary.

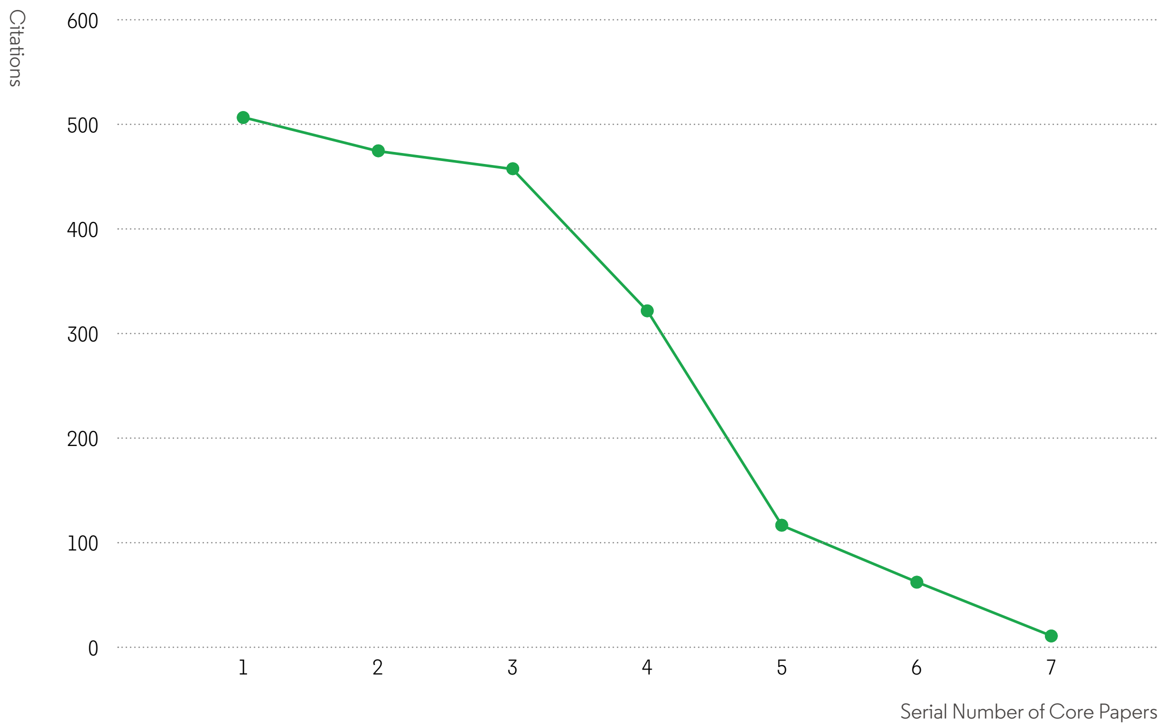
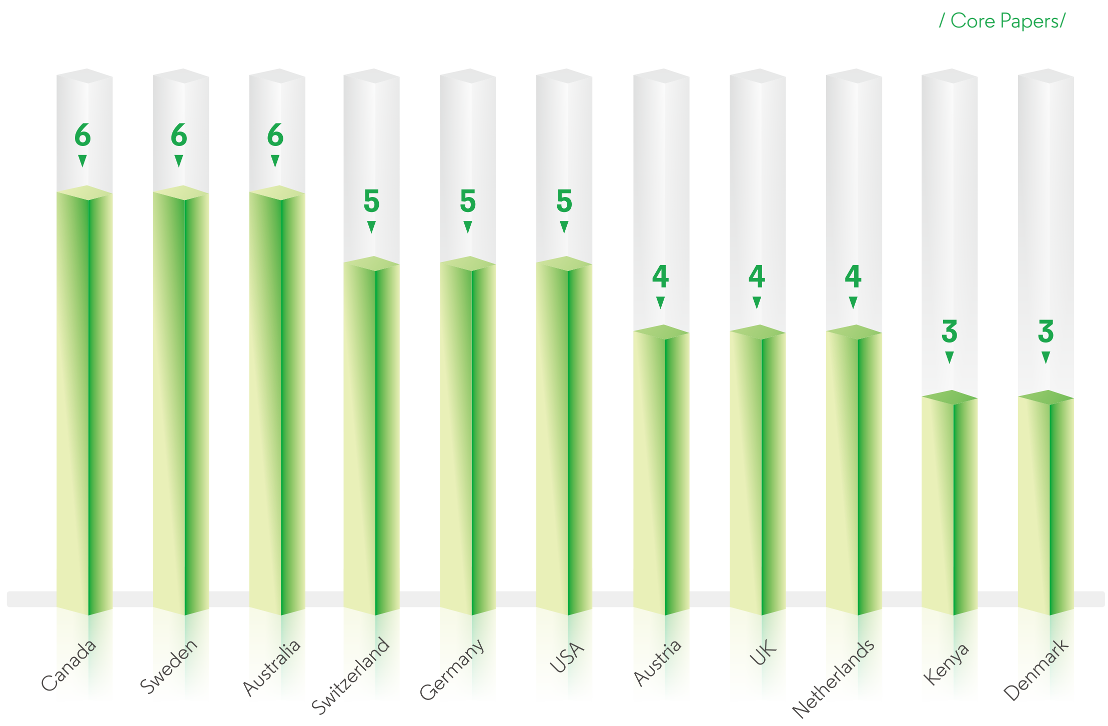


Figure 5: Citation frequency distribution curve of core papers in the Research Front "Planetary boundaries transgression and Earth system risk governance"

Regarding the countries and institutions behind the core papers (Table 8): the European nations and the USA are the primary contributors to this hot front. Among them, Sweden, Canada, and Australia have produced the most core papers, each contributing six. Switzerland, Germany, and the USA follow closely, each having published five papers. The core papers in this front primarily come from renowned research institutions in areas such as international sustainable development and climate change. Among them, Stockholm University in Sweden has contributed the highest number of core papers, ranking 1st, while the Potsdam Institute for Climate Impact Research in Germany and the Australian National University rank 2nd and 3rd, respectively.

Table 8: Top countries and institutions producing core papers in the Research Front "Planetary boundaries transgression and Earth system risk governance"

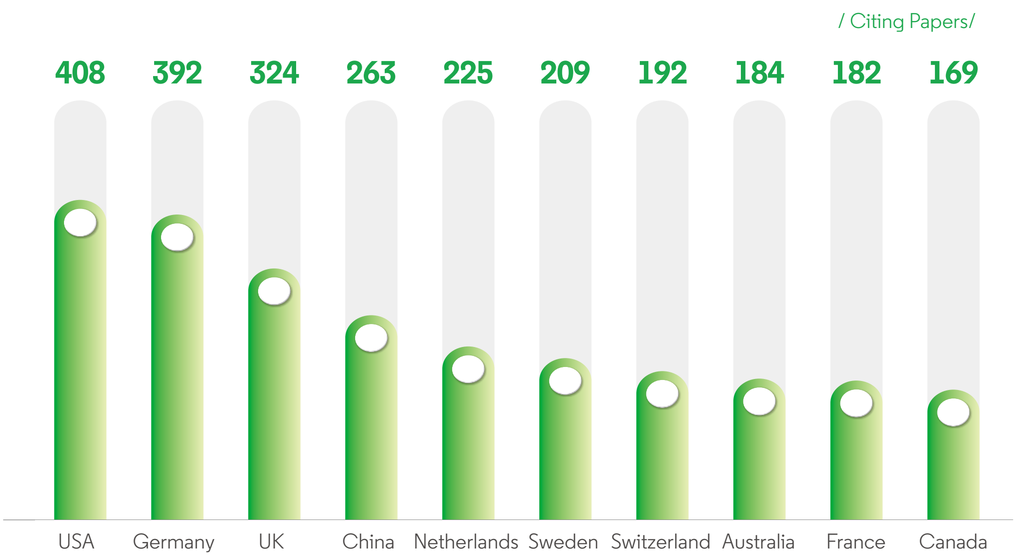
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Canada	6	85.7%	1	Stockholm University	Sweden	6	85.7%
1	Sweden	6	85.7%	2	Potsdam Institute for Climate Impact Research	Germany	5	71.4%
1	Australia	6	85.7%	2	Australian National University	Australia	5	71.4%
4	Switzerland	5	71.4%	4	University of Amsterdam	Netherlands	4	57.1%
4	Germany	5	71.4%	5	Griffith University	Australia	3	42.9%
4	USA	5	71.4%	5	University of Potsdam	Germany	3	42.9%
7	Austria	4	57.1%	5	International Institute for Applied Systems Analysis	Austria	3	42.9%
7	UK	4	57.1%	5	Utrecht University	Netherlands	3	42.9%
7	Netherlands	4	57.1%	5	Royal Swedish Academy of Sciences	Sweden	3	42.9%
10	Kenya	3	42.9%	5	University of Exeter	UK	3	42.9%
10	Denmark	3	42.9%					



In terms of the countries and institutions citing the core papers (Table 9), the USA, Germany, and the UK are the top three contributing countries, each accounting for approximately one-fifth of the total. China produced 263 citing papers, constituting 15.3% of the total and ranking 4th. From the perspective of institutions producing citing papers, the standings are similar to the core-paper institutions: Stockholm University in Sweden remains the top contributor with 96 citing papers, followed closely by the Helmholtz Association in Germany with 94 papers, ranking 2nd. The National Centre for Scientific Research of France (CNRS) and the Chinese Academy of Sciences rank 3rd and 4th, with 79 and 75 citing papers, respectively.

Table 9: Top countries and institutions producing citing papers in the Research Front "Planetary boundaries transgression and Earth system risk governance"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	408	23.7%	1	Stockholm University	Sweden	96	5.6%
2	Germany	392	22.8%	2	Helmholtz Association	Germany	94	5.5%
3	UK	324	18.8%	3	National Center for Scientific Research of France (CNRS)	France	79	4.6%
4	China	263	15.3%	4	Chinese Academy of Sciences	China	75	4.4%
5	Netherlands	225	13.1%	5	Swiss Federal Institute of Technology Zurich	Switzerland	69	4.0%
6	Sweden	209	12.2%	6	Technical University of Denmark	Denmark	54	3.1%
7	Switzerland	192	11.2%	6	Wageningen University & Research Center	Netherlands	54	3.1%
8	Australia	184	10.7%	8	University of London	UK	49	2.8%
9	France	182	10.6%	9	National Research Institute for Agriculture, Food and Environment	France	47	2.7%
10	Canada	169	9.8%	10	University of Exeter	UK	44	2.6%



1.3 KEY HOT RESEARCH FRONT "Preparation of biomass derived porous activated carbon adsorbent and CO_2 capture performance"

Carbon Capture, Utilization, and Storage (CCUS) is an effective method for reducing atmospheric carbon dioxide concentrations and an essential solution for achieving net-zero emissions. Among various carbon capture materials, cost-effective CO_2 adsorbents have garnered significant attention. The adsorption of CO_2 typically requires materials with superior texture and surface properties, or those appropriately functionalized to achieve high adsorption capacity. Among adsorption materials, porous carbon-based materials and ordered nanoporous materials are the most prevalent. Biomass can be pyrolyzed under anaerobic conditions to produce biochar.

By adding activators before or after the preparation of biochar, activated porous carbon materials with higher specific surface areas and more developed porosity can be obtained. Biomass-derived porous carbon is regarded as a preferred CO_2 adsorbent due to its excellent textural properties, tunable porosity, low cost, relatively simple and feasible synthesis methods, and high CO_2 adsorption capacity.

Twenty-six core papers anchor this hot front, mainly focusing on methods for preparing surface-modified porous carbon materials doped with heteroatoms such as nitrogen and sulfur, using various biomass wastes as raw materials and employing different activation methods and activators. The material synthesis approaches are green, simple, cost-effective, and can achieve highly efficient and highly selective carbon dioxide adsorption, capture, and separation.

The most frequently cited core paper in this front is from Nanjing Normal University, China, published in 2020 in the *Chemical Engineering Journal*, with nearly 367 citations to date. The authors used different activators (air, carbon dioxide, phosphoric acid, and sodium hydroxide) to prepare activated porous carbon from bagasse. Compared to physically activated carbon, the chemically activated porous carbon exhibited superior physicochemical properties and excellent CO_2 adsorption performance.

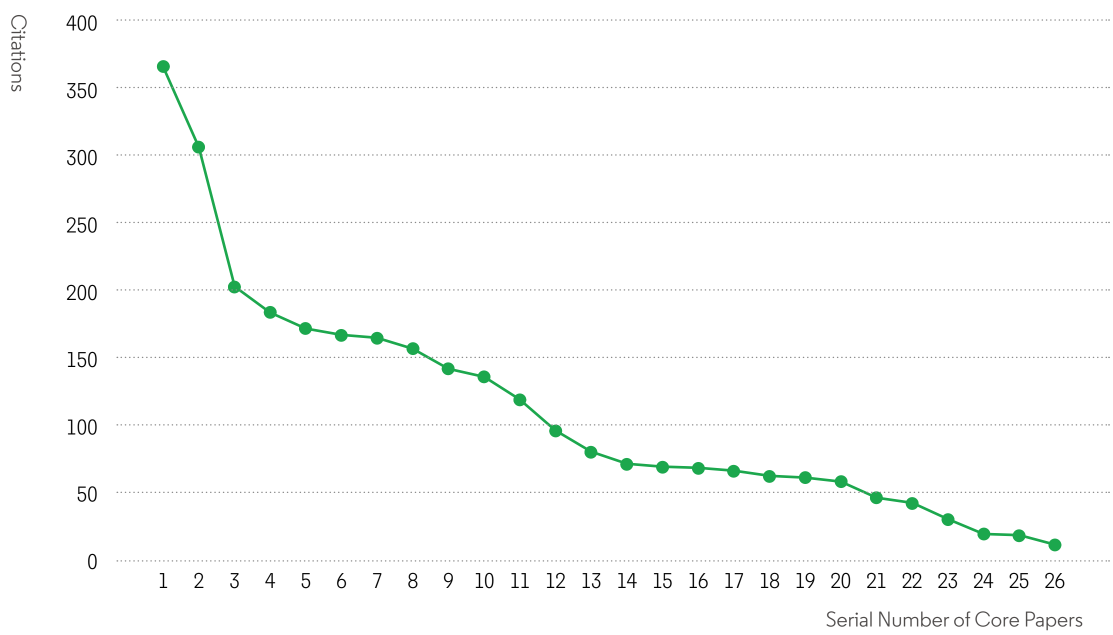
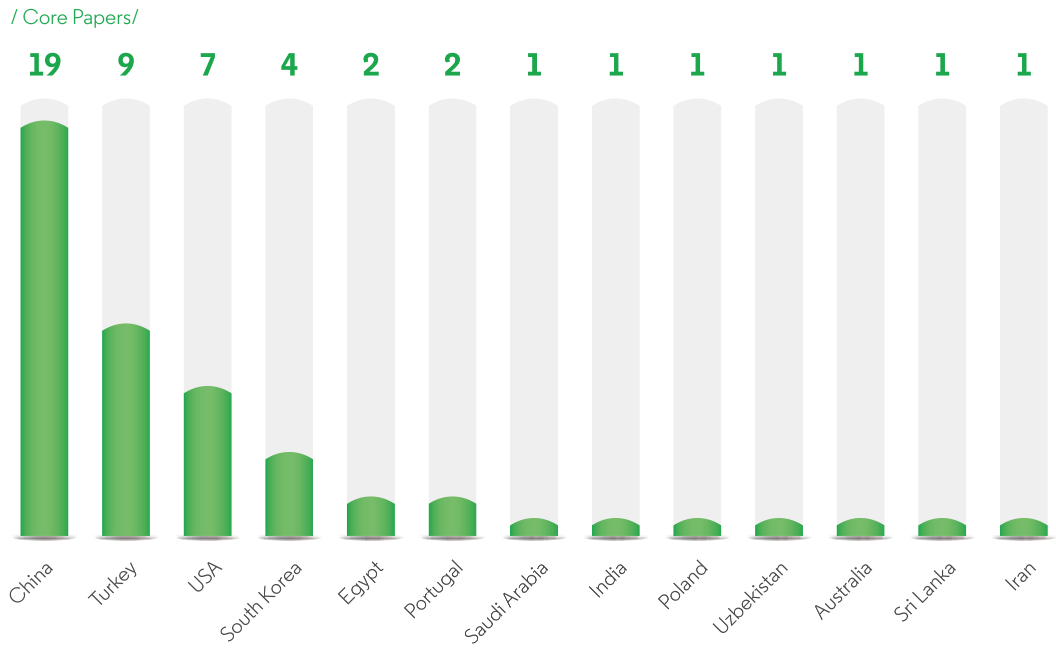


Figure 6: Citation frequency distribution curve of core papers in Research Front "Preparation of biomass derived activated porous carbon adsorbent and CO_2 capture performance"

Statistics on the countries and institutions in this front (Table 10) indicate that China holds a dominant position in this front, being the largest contributor of core papers with a total of 19 publications, accounting for nearly three-quarters of the total core reports. Turkey contributed nine core papers, exceeding one third of the total and jointly ranking 2nd. The USA has seven core articles, accounting for more than a quarter of the total, ranking 3rd. Among the publishing institutions, Zhejiang Normal University published 10 core papers, accounting for over one-third of the total, ranking 1st. Turkish research institutions also demonstrate notable performance, with the Scientific and Technological Research Council of Turkey and Osmaniye Korkut Ata University each contributing six core papers, tying for second place. The Chinese Academy of Sciences ranks 5th.

Table 10: Top countries and institutions producing core papers in the Research Front "Preparation of biomass derived activated porous carbon adsorbent and CO_2 capture performance"

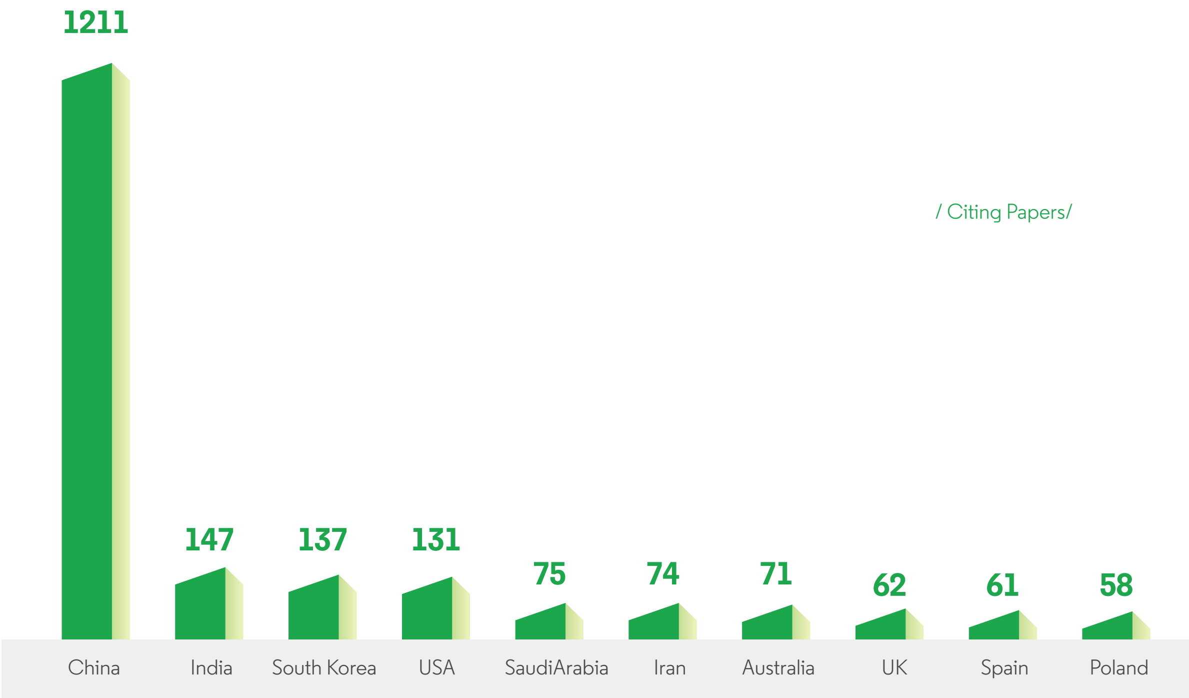
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	19	73.1%	1	Zhejiang Normal University	China	10	38.5%
2	Turkey	9	34.6%	2	TUBITAK	Turkey	6	23.1%
3	USA	7	26.9%	2	Osmaniye Korkut Ata Univerisity	Turkey	6	23.1%
4	South Korea	4	15.4%	4	Bogazici University	Turkey	4	15.4%
5	Egypt	2	7.7%	5	Chinese Academy of Sciences	China	3	11.5%
5	Portugal	2	7.7%	5	Rochester Institute of Technology	USA	3	11.5%
7	Saudi Arabia	1	3.8%	5	Inha University	South Korea	3	11.5%
7	India	1	3.8%	8	University of Science and Technology of China	China	2	7.7%
7	Poland	1	3.8%	8	Sichuan University	China	2	7.7%
7	Uzbekistan	1	3.8%	8	Wuhan University of Technology	China	2	7.7%
7	Australia	1	3.8%	8	Assiut University	Egypt	2	7.7%
7	Sri Lanka	1	3.8%	8	Instituto Politécnico de Bragança	Portugal	2	7.7%
7	Iran	1	3.8%	8	University of Porto	Portugal	2	7.7%
				8	Kyung Hee University	South Korea	2	7.7%
				8	Iskenderun Technical University	Turkey	2	7.7%
				8	Argonne National Laboratory	USA	2	7.7%
				8	University of Chicago	USA	2	7.7%
				8	University of Nebraska–Lincoln	USA	2	7.7%



From the perspective of citing papers by country and institution (Table 11), China demonstrates the most active follow-up research in this area, publishing 1,211 citing papers, accounting for over 60% of the total, far surpassing other countries. India and South Korea rank 2nd and 3rd with 147 and 137 citing papers, respectively. Regarding the institutions generating citing papers, the top ten are all based in China. Among them, the Chinese Academy of Sciences leads by a significant margin with 121 citing papers, while Central South University and Nanjing University of Technology are tied for second with 55 citing papers each.

Table 11: Top countries and institutions producing citing papers in the Research Front "Preparation of biomass derived activated porous carbon adsorbent and CO_2 capture performance"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1211	61.2%	1	Chinese Academy of Sciences	China	121	6.1%
2	India	147	7.4%	2	Central South University	China	55	2.8%
3	South Korea	137	6.9%	2	Nanjing University of Technology	China	55	2.8%
4	USA	131	6.6%	4	Sichuan University	China	54	2.7%
5	Saudi Arabia	75	3.8%	5	Wuhan University of Technology	China	44	2.2%
6	Iran	74	3.7%	6	University of Science and Technology of China	China	42	2.1%
7	Australia	71	3.6%	7	Zhejiang Normal University	China	39	2.0%
8	UK	62	3.1%	8	Taiyuan University of Technology	China	37	1.9%
9	Spain	61	3.1%	9	Huazhong University of Science & Technology	China	32	1.6%
10	Poland	58	2.9%	9	Nanjing Forestry University	China	32	1.6%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN ECOLOGY AND ENVIRONMENTAL SCIENCES

The area of ecology and environmental sciences features one emerging Research Front: "Microbial mechanisms of volatile fatty acids generation from sludge anaerobic fermentation" (Table 12).

Table 12: Emerging Research Fronts in ecology and environmental sciences

Rank	Emerging Research Fronts	Core papers	Citations	Mean Year of Core Papers
1	Microbial mechanisms of volatile fatty acids generation from sludge anaerobic fermentation	5	148	2023.6

2.2 KEY EMERGING RESARCH FRONT "Microbial mechanisms of volatile fatty acids generation from sludge anaerobic fermentation"

The waste activated sludge (WAS) generated from wastewater treatment is rich in complex organic matter and diverse microorganisms, making it a primary organic substrate for producing high-value volatile fatty acids (VFAs). Anaerobic fermentation is a key pathway for promoting VFAs production from WAS and enabling efficient resource recovery. However, its overall efficiency is often limited by undesirable inhibitors. Meanwhile, to enhance the release of dissolved organic matter from WAS and thereby promote VFAs synthesis, various pretreatment methods are commonly employed, including the addition of pretreatment agents.

Five core papers in this emerging front focus on the complex interrelationships among the dynamic changes of dissolved organic matter and bacterial community networks, assembly processes, and microbial characteristics during WAS fermentation. The studies investigate the processes and mechanisms by which various antimicrobial agents (such as the broad-spectrum bactericide zinc pyrithione and methylisothiazolinone) and activated sludge pretreatment methods (like choline chloride and tannic acid treatment) promote substrate utilization, regulate microbial communities and metabolic characteristics, and enhance volatile fatty acid production. The studies have developed pretreatment methods for WAS fermentation and elucidated the environmental behavior of emerging pollutants in the anaerobic digestion process of WAS, as well as the interrelationships between microbial metabolic regulation and adaptive responses.

2025
RESEARCH FRONTS

04
GEOSCIENCES

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN GEOSCIENCES

In 2025, among the Top 10 Research Fronts in geosciences, five are in geology, two in atmospheric science, two in geography, and one in planetary science. Overall, the focus is on energy and resource security, extreme climate events, and the application of advanced technologies.

In the field of geology, "Types of shale oil in China's continental basins and resource potential in key regions" and "Progress in advanced separation and recovery techniques for rare earth elements" address strategic priorities related to national energy security. These topics have drawn increasing attention from governments worldwide.

In atmospheric science, "Global impact of the Tonga volcanic eruption" and "Causes and climate risks of flash drought events" reflect a deepening scientific understanding of abrupt changes in the climate system and the risks of extreme events. In planetary science, a Research Front centered on "Analysis of asteroid surface characteristics and sample composition" has appeared in this annual report for four consecutive years. At the same time, Research Fronts such as "Hydrological and water resources prediction based on machine learning", "Holocene temperature conundrum", and "Radiocarbon age calibration curves, data sets, and applications" have also been featured multiple times, highlighting the sustained academic commitment to advancing the fundamental scientific research aimed at expanding the boundaries of knowledge in the geosciences.

Table 13: Top10 Research Fronts in geosciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Global impact of the Tonga volcanic eruption	21	2124	2021.9
2	**Types of shale oil in China's continental basins and resource potential in key regions**	**45**	**5073**	**2021.8**
3	Assessment of the impact of extreme drought on European forests	9	1355	2021.6
4	**Causes and climate risks of flash drought events**	**8**	**1296**	**2021.4**
5	Progress in advanced separation and recovery techniques for rare earth elements	19	3112	2021.3
6	Hydrological and water resources prediction based on machine learning	18	2387	2021.3
7	Carbon flux in the ocean biological pump	7	1007	2021.3
8	Radiocarbon age calibration curves, data sets, and applications	7	6064	2021.1
9	Holocene temperature conundrum	24	3557	2020.9
10	Analysis of asteroid surface characteristics and sample composition	18	3072	2020.9

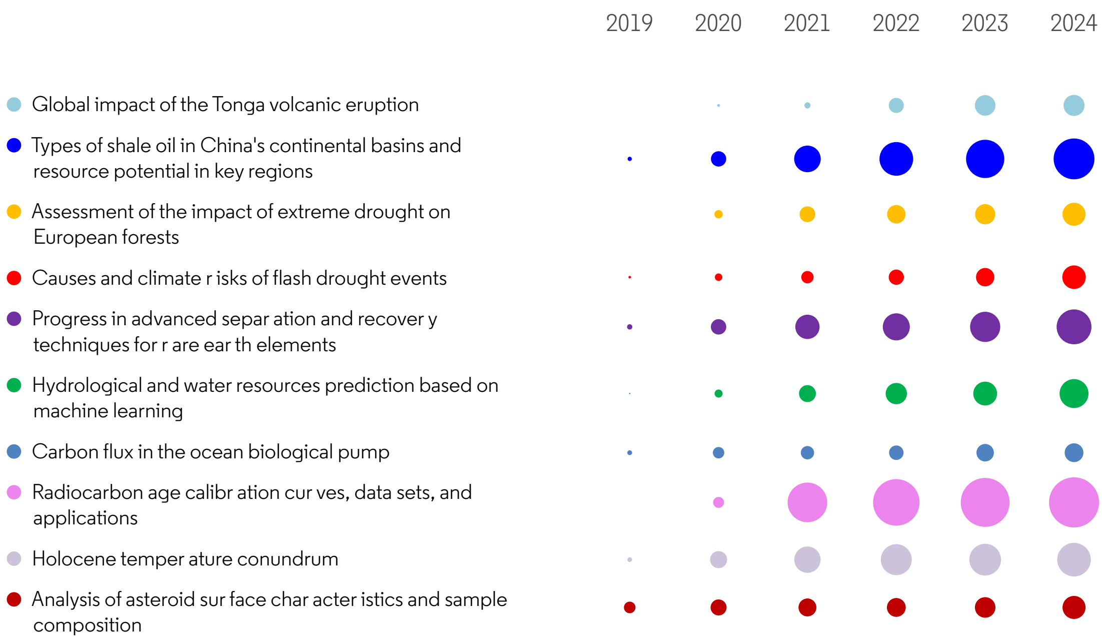


Figure 7: Citing papers for the Top 10 Research Fronts in geosciences

1.2 KEY HOT RESEARCH FRONT – "Types of shale oil in China's continental basins and resource potential in key regions"

Shale oil refers to petroleum resources contained within organic-rich shale formations, encompassing hydrocarbons stored in the pores and fractures of mud shale as well as in thin interbedded carbonate or clastic rocks within the shale sequence. Unlike the marine shale oil widely distributed in North America, China's proven shale-oil resources are predominantly hosted in continental organic-rich mud shale formations. With substantial resource potential, this asset is regarded as a key replacement domain to support China's sustained crude oil growth and long-term stable production, serving as a "ballast stone" in the country's national energy-security strategy.

In 2022, China's continental shale oil production reached approximately 3.18 million tons, accounting for 1.6% of the nation's total crude oil output. Due to the heterogeneous distribution characteristics of continental shale, shale oil types vary significantly among different basins in China. At present, petroleum enterprises and research institutions have proposed multiple classification schemes for continental shale oil based on parameters such as depositional environment, phase state, reservoir type, thermal maturity, lithologic assemblage, and source–reservoir configuration. However, a unified classification standard has yet to be established.

In recent years, China has successively achieved a series of shale oil exploration breakthroughs in several typical organic-rich shale formations within major continental sedimentary basins. These include the Permian Lucaogou and Fengcheng formations in the Junggar Basin, the

Triassic Chang 7 Member of the Yanchang Formation in the Ordos Basin, the Paleogene Shahejie and Kongdian formations in the Bohai Bay Basin, the Cretaceous Qingshankou Formation in the Songliao Basin, the Jurassic Da'anzhai Formation in the Sichuan Basin, and the Paleogene Qianjiang and Xingouzui formations in the Jianghan Basin.

This hot Research Front includes 45 core papers focusing on the occurrence mechanisms of continental shale oil, pore characteristics of shale reservoirs, geochemical redox proxies, enrichment evaluation methods, and exploration and extraction technologies. The three most-cited papers were all produced by a China–U.S. research team led by Thomas Algeo, Distinguished Professor at China University of Geosciences and faculty member at the University of Cincinnati. "Elemental proxies for paleosalinity analysis of ancient shales and mudrocks", published in *Geochimica et Cosmochimica Acta*, has been cited nearly 350 times to date. This report established three elemental ratios thresholds and validated their effectiveness in reconstructing paleosalinity for ancient continental shales from the Ordos Basin in North China and the mid-Eocene Bohai Bay Basin in NE China.

Another paper, "Redox classification and calibration of redox thresholds in sedimentary systems" (200-plus citations), proposed a novel approach to improve the calibration of such proxies. One important finding of this study is that the threshold value associated with a given elemental proxy can vary considerably between depositional systems. "A re-assessment of elemental proxies for paleoredox analysis", published in *Chemical Geology*, evaluated 21 elemental redox proxies and used principal component analysis to reveal their dependence on mineralization facies.

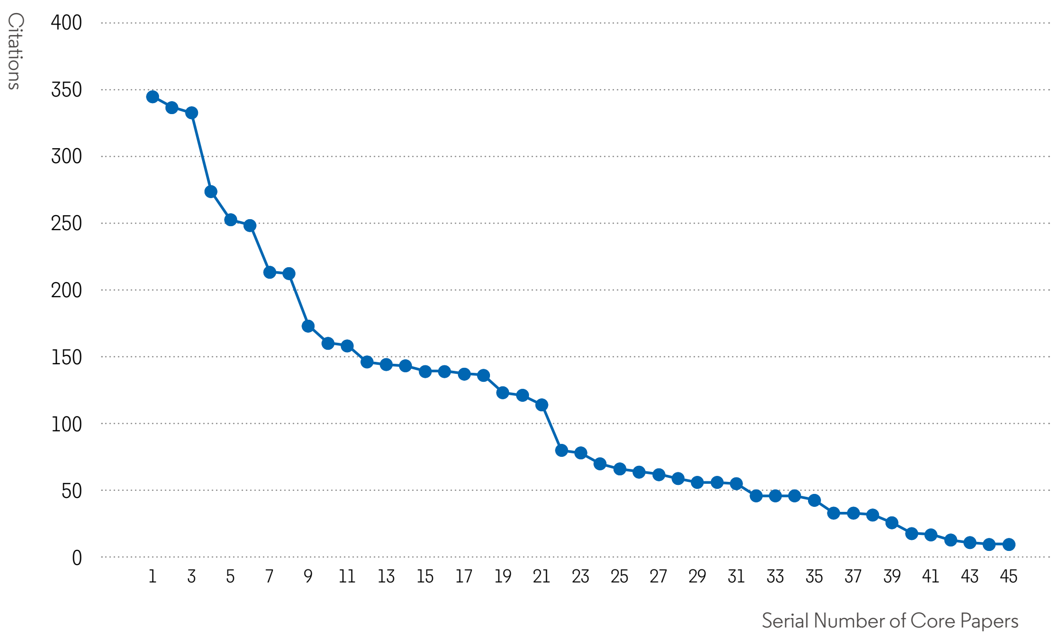
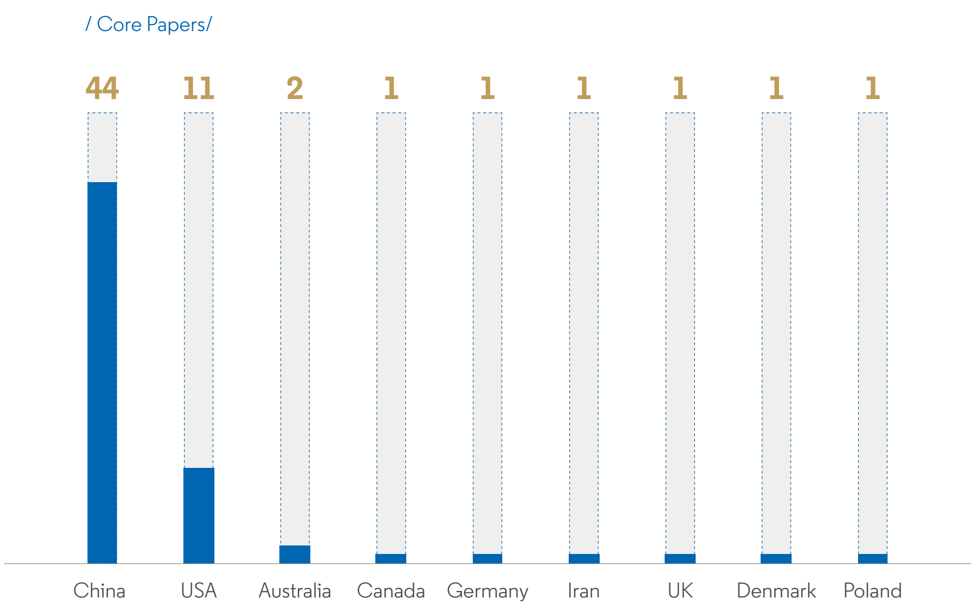


Figure 8: Citation frequency distribution curve of core papers in the Research Front "Types of shale oil in China's continental basins and resource potential in key regions"

In this Research Front, China actively collaborated with partners from the USA, Australia, Canada, Germany, Iran, the UK, and Poland, co-authoring 44 core papers. Among them, all 11 papers published by US-based institutions were the results of collaboration with China. In addition, Australia and Denmark jointly contributed one paper. From an institutional perspective, China National Petroleum Corporation stands out as the most active contributor, accounting for 35.6% of the core papers, followed by China University of Geosciences (Wuhan), Sinopec, and Northeast Petroleum University.

Table 14: Top countries and institutions producing core papers in the Research Front "Types of shale oil in China's continental basins and resource potential in key regions"

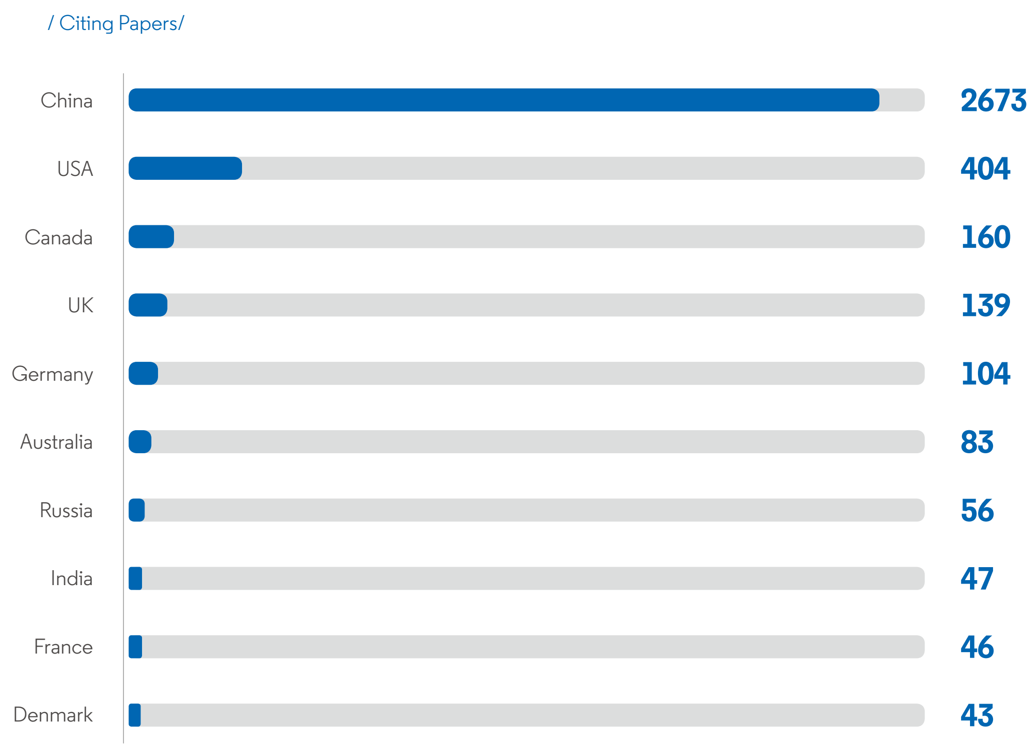
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	44	97.8%	1	China National Petroleum Corporation	China	16	35.6%
2	USA	11	24.4%	2	China University of Geosciences - Wuhan	China	12	26.7%
3	Australia	2	4.4%	3	Sinopec	China	11	24.4%
4	Canada	1	2.2%	4	Northeast Petroleum University	China	10	22.2%
4	Germany	1	2.2%	5	Southwest Petroleum University	China	7	15.6%
4	Iran	1	2.2%	6	Sichuan College of Architectural Technology	China	5	11.1%
4	UK	1	2.2%	7	Chinese Academy of Sciences	China	4	8.9%
4	Denmark	1	2.2%	7	Peking University	China	4	8.9%
4	Poland	1	2.2%	7	University of Cincinnati	USA	4	8.9%
				10	Xi'an Shiyou University	China	3	6.7%
				10	Natural Gas Geology Key Laboratory of Sichuan Province	China	3	6.7%
				10	China University of Petroleum	China	3	6.7%



As for countries producing the most citing papers, China ranks 1st by a significant margin, followed by the USA and Canada. In terms of institutions producing the citing papers, China National Petroleum Corporation performed most prominently. China University of Petroleum and China University of Geosciences (Wuhan) rank 2nd and 3rd, respectively.

Table 15: Top countries and institutions producing citing papers in the Research Front "Types of shale oil in China's continental basins and resource potential in key regions"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	2673	84.6%	1	China National Petroleum Corporation	China	825	26.1%
2	USA	404	12.8%	2	China University of Petroleum	China	649	20.6%
3	Canada	160	5.1%	3	China University of Geosciences - Wuhan	China	484	15.3%
4	UK	139	4.4%	4	Sinopec	China	418	13.2%
5	Germany	104	3.3%	5	Chinese Academy of Sciences	China	372	11.8%
6	Australia	83	2.6%	6	Northeast Petroleum University	China	245	7.8%
7	Russia	56	1.8%	7	Southwest Petroleum University	China	227	7.2%
8	India	47	1.5%	8	China Geological Survey	China	190	6.0%
9	France	46	1.5%	9	Chengdu University of Technology	China	162	5.1%
10	Denmark	43	1.4%	10	Peking University	China	149	4.7%



1.3 KEY HOT RESEARCH FRONT – "Causes and climate risks of flash drought events"

The concept of flash drought was first proposed in 2002 by American scientist Mark D. Svoboda to describe drought conditions that intensify rapidly over a short period. However, it was not until 2012, when a severe flash drought swept across the US Midwest, that the phenomenon sparked a global research boom. Characterized by its abrupt onset and rapid intensification, flash drought threatens severe impacts and often coincides with heatwaves, forming compound extreme events with amplified destructive power. From the Great Plains of North America to the Yangtze River Basin in China, and across Australia's agricultural and pastoral regions, flash droughts have caused massive economic losses and ecological damage, thereby emerging as a global scientific and policy issue.

The formation and evolution of flash droughts are driven by complex interactions among the atmosphere, ocean, and land surface systems, influenced by large-scale circulation anomalies as well as local meteorological, hydrological, soil, vegetation, and topographic conditions. In the context of global climate change, the synergistic and amplifying effects among these processes jointly shape the spatiotemporal distribution patterns and long-term evolution trends of flash droughts.

The eight core papers in this Research Front center on the identification, mechanisms, spatiotemporal evolution, climate impacts, prediction, and risk assessment of flash droughts. The most-cited study, "Anthropogenic shift towards higher risk of flash drought over China" published in *Nature Communications* by Nanjing University of Information Science and Technology, proposes a new method for explicitly characterizing flash drought events. The results reveal that human-induced climate change is the primary driver of increased flash drought frequency. And by the middle of this century, the exposure risk over China will increase by about 23%. Another influential paper, "Flash droughts present a new challenge for subseasonal-to-seasonal prediction" published in *Nature Climate Change* by the US National Center for Atmospheric Research, discusses the challenges in predicting flash droughts, evaluates current forecasting capabilities, and introduces two definitions for incorporating flash droughts into early warning systems and risk management.

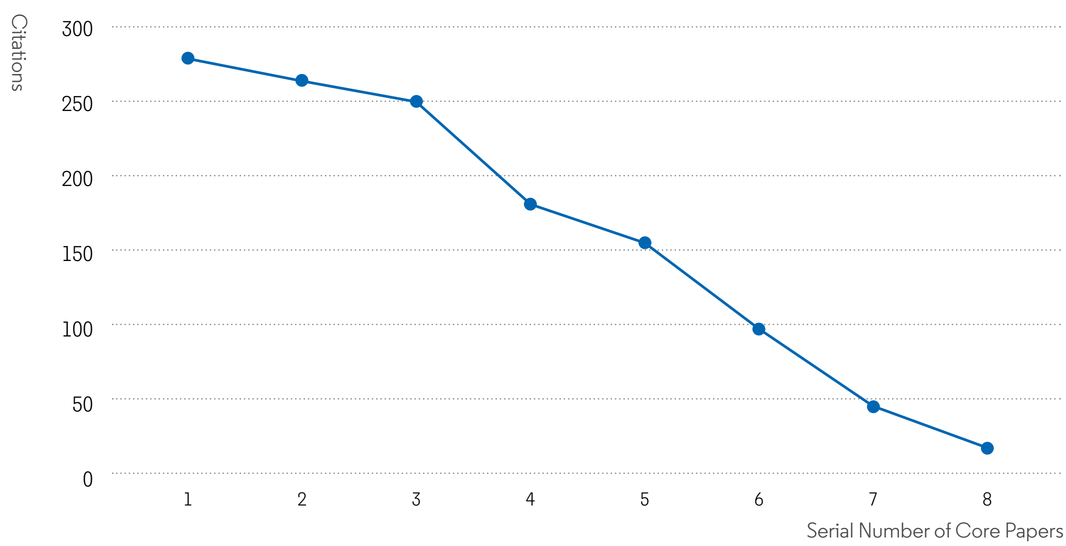
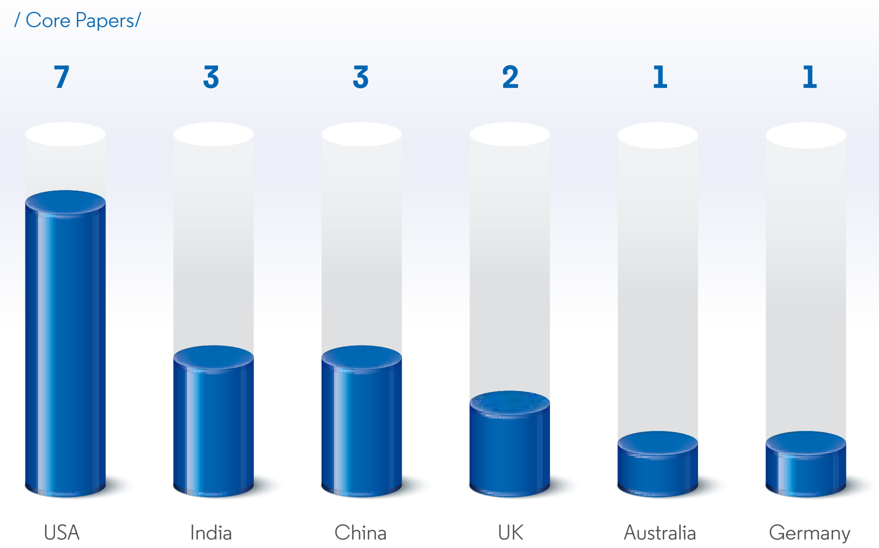


Figure 9: Citation frequency distribution curve of core papers in Research Front "Causes and climate risks of flash drought events"

In this Research Front, the USA demonstrates the highest level of research activity, contributing 87.5% of the total core papers. The University of Wisconsin at Madison, the University of Oklahoma, and the University of Nebraska–Lincoln, all strong in atmospheric science in the USA, rank as the top three contributing organizations. In addition, research institutions such as the Indian Institute of Technology, Nanjing University of Information Science and Technology, and the University of Southampton, have also carried out related research (Table 16).

Table 16: Top countries and institutions producing core papers in the Research Front "Causes and climate risks of flash drought events"

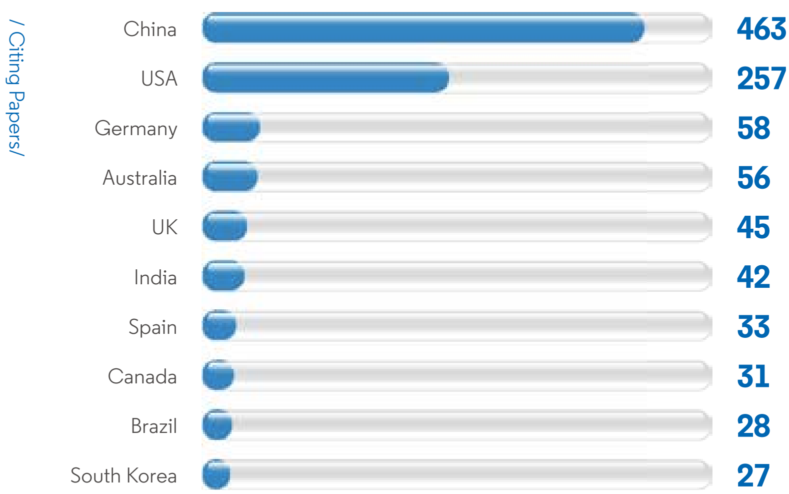
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	7	87.5%	1	University of Wisconsin Madison	USA	5	62.5%
2	India	3	37.5%	2	University of Oklahoma	USA	4	50.0%
2	China	3	37.5%	3	University of Nebraska–Lincoln	USA	3	37.5%
4	UK	2	25.0%	3	Indian Institute of Technology (IIT)	India	3	37.5%
5	Australia	1	12.5%	5	University of Southampton	UK	2	25.0%
5	Germany	1	12.5%	5	National Oceanic Atmospheric Admin (NOAA)	USA	2	25.0%
				5	University of Colorado Boulder	USA	2	25.0%
				5	Nanjing University of Information Science & Technology	China	2	25.0%



As for countries producing the most citing papers (Table 17), China far outpaces all others, reflecting its strong research focus and sustained attention to this front, followed by the USA, Germany, and Australia. Among the top citing institutions, the Chinese Academy of Sciences ranks 1st with 156 citing papers. Other leading contributors include Nanjing University of Information Science and Technology, Beijing Normal University, Wuhan University, Hohai University, and Sun Yat-sen University, all showing outstanding performance. The University of Wisconsin Madison ranks 3rd.

Table 17: Top countries and institutions producing citing papers in the Research Front "Causes and climate risks of flash drought events"

Country Ranking	Country	Citing Paper	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	463	57.3%	1	Chinese Academy of Sciences	China	156	19.3%
2	USA	257	31.8%	2	Nanjing University of Information Science & Technology	China	94	11.6%
3	Germany	58	7.2%	3	University of Wisconsin Madison	USA	35	4.3%
4	Australia	56	6.9%	4	Beijing Normal University	China	33	4.1%
5	UK	45	5.6%	5	Wuhan University	China	31	3.8%
6	India	42	5.2%	6	Hohai University	China	29	3.6%
7	Spain	33	4.1%	7	Sun Yat Sen University	China	28	3.5%
8	Canada	31	3.8%	7	University of Nebraska-Lincoln	USA	28	3.5%
9	Brazil	28	3.5%	9	Indian Institute of Technology (IIT)	India	26	3.2%
10	South Korea	27	3.3%	10	National Aeronautics & Space Administration (NASA)	USA	25	3.1%
				10	University of Colorado Boulder	USA	25	3.1%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN GEOSCIENCES

"Regional extreme precipitation and landslide dynamic model in China" was selected as the emerging Research Front in Geosciences for 2025.

Table 18: Emerging Research Front in geosciences

Rank	Emerging Research Front	Core papers	Citations	Mean Year of Core Papers
1	Regional extreme precipitation and landslide dynamic model in China	8	185	2023.8

2.2 KEY EMERGING RESEARCH FRONT – "Regional extreme precipitation and landslide dynamic model in China"

Against the backdrop of increasingly severe global climate change, extreme precipitation events have become frequent, and the resulting geological disasters, such as landslides, pose a serious threat to people's lives and property as well as socioeconomic development. The emerging front, "Regional extreme precipitation and landslide dynamic model in China", comprises eight research papers focusing on identifying the moisture sources and dynamic causes of extreme precipitation, and provides an in-depth analysis of the specific physical mechanisms of rainfall-triggered landslides.

By constructing and applying a coupled hydrological-geotechnical dynamic models, this research quantitatively reveals the physical mechanisms and spatiotemporal evolution of landslides triggered by extreme precipitation in specific regions. In the future, this work is expected to be widely applied in disaster early warning, climate change adaptation planning, safety assurance for major engineering projects, and national emergency management.

Among the core literature in this front, a paper published in *Geophysical Research Letters* overturned the traditional view that moisture in the arid region of Northwest China is entirely dependent on external transport. The study found that in the increments of extreme precipitation in Xinjiang, the contribution of local recycling (49%) is almost as important as that of external transport (51%), providing a key physical mechanism for understanding the "warming and wetting" trend in the northwest region.

A publication in *Geoscientific Model Development* achieved a significant model breakthrough by proposing a full-chain simulation tool, i.e., the iHydroSlide3D model, which simulates the entire process from rain to slope. This model has successfully reproduced flood-landslide cascade events in several basins. Another comprehensive study, spanning 15 years, pointed out that with the increase of extreme weather events in recent years, the dominant factor controlling landslide deformation is gradually shifting from the relatively predictable reservoir water-level fluctuations to the more sudden and intense extreme rainfall. Simultaneously, the failure mode of landslides is evolving into a compound pattern characterized by thrusting and overall translation. This profound insight has significant implications for guiding long-term geological risk management and early warning in large-scale hydraulic engineering areas.

Furthermore, other major breakthroughs in this emerging Research Front include: comparing different weather patterns to identify the differences in dynamic mechanisms, such as the upper-level jet stream and baroclinic troughs, that drive heavy rainfall in North China; determining that moisture transport from the West Pacific is the decisive factor causing "atmospheric river" type extreme precipitation in the Yangtze River Basin; constructing an intelligent fluid-solid coupling model (CFD-DEM) to simulate siltation in urban drainage pipelines, providing a new tool for urban flood control; deriving a more precise analytical solution for the rainfall infiltration-deformation coupling problem for specific bedrock slopes; and, for the first time, identifying and quantifying a new type of compound disaster known as the "sudden turn from drought to flood" (STDF) and revealing its increasing trend and different regional driving mechanisms in China.

2025

RESEARCH FRONTS

05

CLINICAL MEDICINE

1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN CLINICAL MEDICINE

The Top 10 Research Fronts in clinical medicine for 2025 focus mainly on the prevention and treatment of diseases such as cancer, respiratory infectious diseases, Alzheimer's, cystic fibrosis, and depression, as well as the development and application of artificial intelligence (AI) technologies in medicine.

In the realm of cancer treatment, research efforts have placed significant emphasis on the application of immunotherapy, targeted therapy, and combination therapies across various cancer types, encompassing five key research concentrations, including "Immunotherapy and combined therapy for advanced cervical cancer". These efforts continue the research momentum observed in recent years regarding immune and molecular targeted therapies for complex conditions like malignancies.

Moreover, the front entitled "Vaccines and monoclonal antibodies for the prevention of respiratory syncytial virus infection" highlights advancements in infectious disease prevention. Meanwhile, "Clinical validation and safety management of anti-amyloid protein targeted therapies for early Alzheimer's disease" focuses on targeted treatments and clinical management strategies for Alzheimer's and other neurodegenerative disorders.

CFTR modulator triple therapy represents a milestone in the treatment of cystic fibrosis, transforming the malady from a progressive and fatal condition that could only be treated symptomatically into a chronic disease that can be effectively controlled and managed. This achievement marks a pivotal shift from symptom alleviation to addressing the underlying etiology.

Elsewhere on the list of hot Research Fronts: "Efficacy of psilocybin in treating depression" explores the potential of the traditional hallucinogen psilocybin as a novel therapeutic option for depression, involving comprehensive studies on its effectiveness, mechanisms of action, and safety profile.

Furthermore, with the rapid advancement of AI, its application in the field of clinical medicine is gaining increasing research attention. From last year's focus on "Artificial intelligence and dentistry" to this year's exploration of "Weakly-supervised deep learning framework for whole-slide pathological images", AI is predicted to profoundly reshape future clinical diagnosis and treatment paradigms.

Table 19: Top10 Research Fronts in clinical medicine

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Vaccines and monoclonal antibodies for the prevention of respiratory syncytial virus infection	38	4559	2022.9
2	Immunotherapy and combined therapy for advanced cervical cancer	14	2233	2022.4
3	Breakthroughs in immunotherapy targets and resistance mechanisms for relapsed/refractory multiple myeloma (RRMM)	28	5828	2022.3
4	Clinical validation and safety management of anti-amyloid protein targeted therapies for early Alzheimer's disease	20	5365	2022.3
5	**Triple therapy of CFTR modulators has enabled the transition from symptom control to etiological treatment in cystic fibrosis**	**30**	**4471**	**2022.2**
6	Precision treatment for operable non-small cell lung cancer (NSCLC): a dual strategy of targeted and immunotherapy	41	8183	2022.1
7	Efficacy of psilocybin in treating depression	11	2469	2022.1
8	Efficacy of dual immune checkpoint blockade (PD-1/LAG-3) in neoadjuvant and adjuvant treatments for melanoma	23	4983	2021.5
9	Combined immunotherapy for advanced hepatocellular carcinoma	29	15779	2021.3
10	**Weakly-supervised deep learning framework for whole-slide pathological images**	**29**	**6537**	**2021.1**

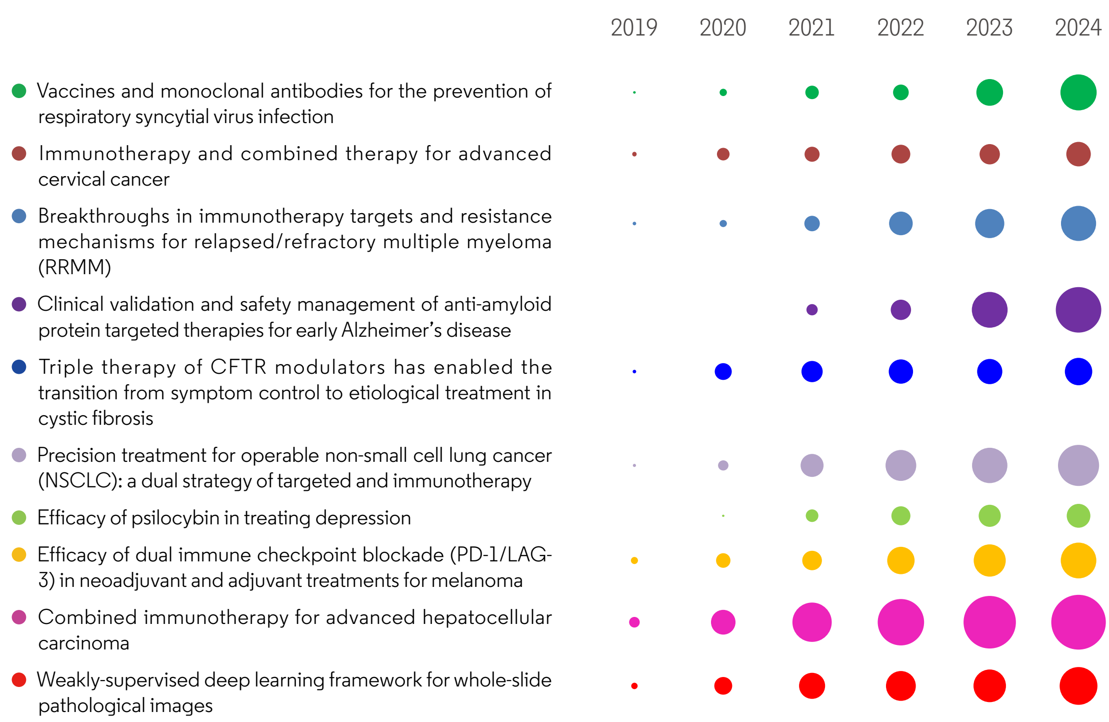


Figure 10: Citing papers for the Top10 Research Fronts in clinical medicine

1.2 KEY HOT RESEARCH FRONT – "Triple therapy of CFTR modulators has enabled the transition from symptom control to etiological treatment in cystic fibrosis"

Cystic fibrosis (CF) is a common and fatal genetic disorder caused by mutations in the gene encoding the cystic fibrosis transmembrane conductance regulator (CFTR). CFTR is widely expressed on the cell surface of epithelial cells and regulates water and salt balance in various tissues and organs in the body. The absence or abnormality of CFTR can lead to malnutrition, liver diseases, recurrent bacterial infections, chronic inflammation, and respiratory failure.

Previous medical approaches focused on symptom control, attempting to delay irreversible decline in lung function and the occurrence of complications through measures that included complex physical sputum clearance, high-dose antibiotics to combat infections, and pancreatic enzyme supplements to aid digestion. However, none of these addressed the root cause of the disease—the protein function defect caused by CFTR gene mutations. It was not until the emergence of CFTR modulator triple therapy, known as ETI (Elexacaftor/Tezacaftor/Ivacaftor), that this struggle underwent a fundamental turning point. ETI therapy is a milestone in the treatment of CF. The advent of this revolutionary therapy marks the entry of CF treatment into a new era of precision medicine, shifting from symptom management to addressing the root cause.

The research themes of the 30 core papers in this hot front are highly concentrated, evaluating the efficacy, safety, mechanism of action, and comprehensive clinical impact of ETI therapy on CF patients, in three main areas:

1. Key clinical trials and efficacy validation: These key papers together form the scientific foundation of this groundbreaking therapy, providing a complete chain of clinical validation that supported the US Food and Drug Administration's (FDA) approval of the triple therapy of cystic fibrosis.

In October 2019, the FDA first approved ETI therapy for CF patients aged 12 and over who carry at least one F508del mutation. This decision was mainly based on the results of the phase III clinical trials reported in two key papers published in The New England Journal of Medicine and The Lancet in 2019, which are also the two most frequently cited papers in this Research Front. Together, these two studies constitute the decisive evidence of the effectiveness of ETI therapy for the main CF patient group, and are the primary scientific basis for the initial approval by the FDA.

After the initial approval, subsequent studies expanded the target population to pediatric patients and patients with rare mutations. The key basis for this is a series of in vitro functional studies published in journals such as Journal of Cystic Fibrosis, which demonstrated in cell models that ETI can restore the function of CFTR protein for these rare mutations, reflecting the advanced concept of precision medicine.

2. In-depth exploration of the mechanism of action: This part of the research answers the scientific question "Why is ETI so effective?". Related research reveals the molecular structural basis of "collaborative rescue" of the F508del mutant protein by ETI and confirms at the molecular and cellular levels that ETI not only corrects the F508del mutation but also improves the function of CFTR protein.

3. Real clinical-effect studies: After the approval of ETI, the research focus shifted to the compound's long-term effects in real clinical environments. Multiple registry studies have verified the results of clinical trials in larger and broader patient populations, showing improvements in lung function and reduced hospitalization rates, among other factors.

To sum up: ETI therapy has completely changed the profile and treatment of CF, transforming it from a progressive and fatal disease into a manageable chronic disease, achieving a fundamental leap from "controlling symptoms" to "correcting the cause". In addition, ETI therapy is a successful example of precision medicine. From selecting patients based on their genotypes to using in vitro data to provide individualized treatment plans for patients with rare mutations, the field of CF treatment has become a perfect example of precision medicine from theory to practice.

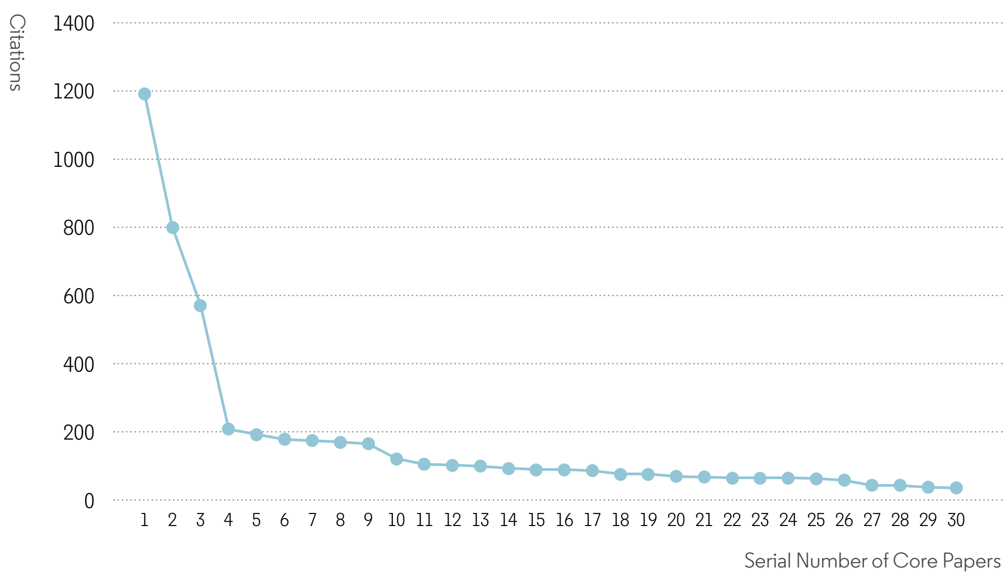
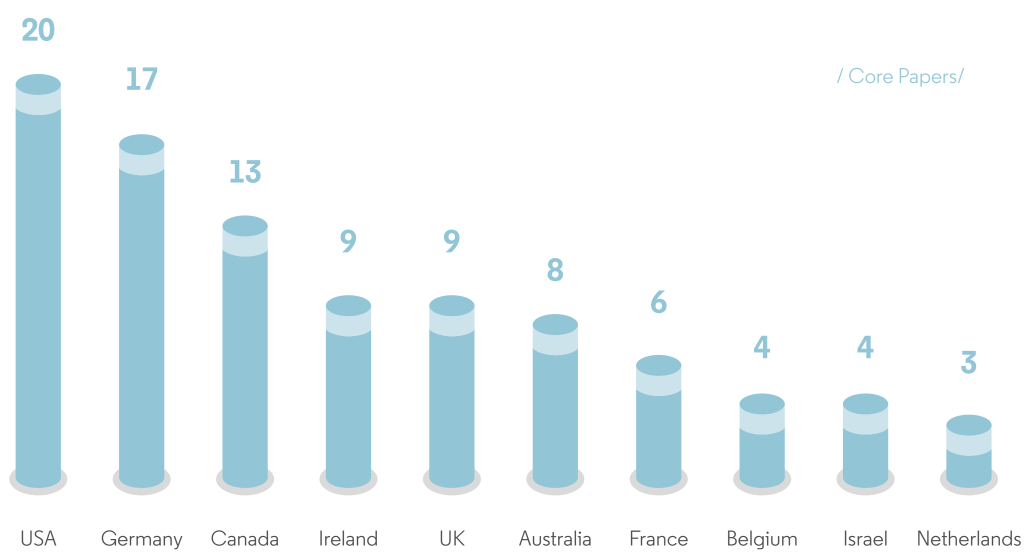


Figure 11: Citation frequency distribution curve of core papers in the Research Front "Triple therapy of CFTR modulators has enabled the transition from symptom control to etiological treatment in cystic fibrosis"

Among the top producing countries of the 30 core papers, the USA had the highest contribution rate, accounting for 66.7%, followed by Germany and Canada. The core papers in this front are mostly typical examples of global multi-center clinical trials, with a very wide and deep participation of countries and institutions. The top-producing institutions bring together leaders in the global CF treatment field, ensuring the broad applicability and authority of the trial results. Among these institutions, Vertex Pharmaceuticals, as the only commercial firm to be highlighted, served as the initiator, funder, and leader of the key registration clinical trials and core mechanism research, and acted as the data provider and drug supplier for the research in some core papers.

Table 20: Top countries and institutions producing core papers in the Research Front "Triple therapy of CFTR modulators has enabled the transition from symptom control to etiological treatment in cystic fibrosis"

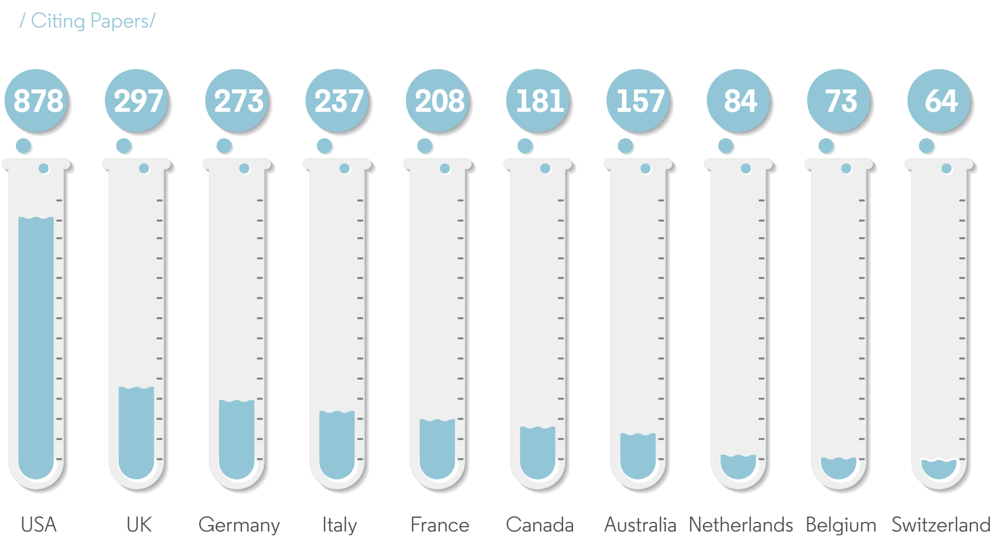
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	20	66.7%	1	Charite Medical University of Berlin	Germany	14	46.7%
2	Germany	17	56.7%	2	University of Toronto	Canada	12	40.0%
3	Canada	13	43.3%	3	University of Washington	USA	11	36.7%
4	Ireland	9	30.0%	3	Vertex Pharma	USA	11	36.7%
4	UK	9	30.0%	5	National Jewish Health	USA	8	26.7%
6	Australia	8	26.7%	5	University of Alabama Birmingham	USA	8	26.7%
7	France	6	20.0%	5	University College Dublin	Ireland	8	26.7%
8	Belgium	4	13.3%	8	Harvard University	USA	5	16.7%
8	Israel	4	13.3%	8	University of Colorado	USA	5	16.7%
10	Netherlands	3	10.0%	8	University of Paris Cite	France	5	16.7%



In terms of the citing papers, the USA contributed the most, accounting for 42.4%, significantly surpassing the second-place country, the UK. Among the top 10 institutions that produced citing papers, two institutions are based in France: the French National Institute of Health and Medical Research, and the University of Paris-Saint-Denis, which are ranked 1st and 2nd, respectively. The University of Washington in the USA tied for 2nd place. The Charite Medical University of Berlin in Germany ranks 4th, while the University of Toronto in Canada ranks 5th. The other five institutions are all from the USA.

Table 21: Top countries and institutions producing citing papers in the Research Front "Triple therapy of CFTR modulators has enabled the transition from symptom control to etiological treatment in cystic fibrosis"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	878	42.4%	1	National Institute of Health and Medical Research (INSERM)	France	150	7.2%
2	UK	297	14.3%	2	University of Paris Cite	France	125	6.0%
3	Germany	273	13.2%	2	University of Washington	USA	125	6.0%
4	Italy	237	11.4%	4	Charite Medical University of Berlin	Germany	95	4.6%
5	France	208	10.0%	5	University of Toronto	Canada	92	4.4%
6	Canada	181	8.7%	6	National Jewish Health	USA	90	4.3%
7	Australia	157	7.6%	7	University of North Carolina Chapel Hill	USA	87	4.2%
8	Netherlands	84	4.1%	8	University of Alabama Birmingham	USA	85	4.1%
9	Belgium	73	3.5%	9	Harvard University	USA	81	3.9%
10	Switzerland	64	3.1%	10	University of Colorado	USA	79	3.8%



1.3 KEY HOT RESEARCH FRONT – "Weakly-supervised deep learning framework for whole-slide pathological images"

The rapid development of digital pathology—converting glass slides of tissue samples into high-resolution digital images—has provided unprecedented opportunities for AI-assisted diagnosis. Whole Slide Images (WSIs), as the basis of pathological diagnosis, usually have extremely high resolution, but also bring huge computational challenges. Traditional deep learning methods demand pixel-level or region-level fine annotations, which require pathologists to invest much time in manual annotation, becoming the main bottleneck restricting the technology's clinical application. Weakly supervised deep learning, on the other hand, utilizes weakly annotated data such as slice-level labels, effectively reducing the reliance on fine annotations, providing a feasible solution for the automation of pathological diagnosis.

The Hot Research Front "Weakly supervised deep learning framework for whole slide pathological images" includes 29 core papers, mainly evaluating the application effect of weakly supervised deep learning frameworks in pathological diagnosis. Overall, weakly supervised deep learning has achieved significant results in many aspects, such as cancer diagnosis and classification, prognosis prediction, and biomarker discovery.

The core paper with the highest citation frequency was published in Nature Medicine in 2019 by researchers at Memorial Sloan Kettering Cancer Center in the USA. It was the first to propose a deep learning system based on the Multiple Instance Learning (MIL) framework, pioneering the application of weakly supervised deep learning in pathology. This procedure requires only slice-level labels, avoiding expensive and time-consuming pixel-level manual annotation, and using a large-scale whole-slide image dataset to evaluate this framework. The results show that this system can train accurate classification models with a sensitivity of up to 100%.

In 2021, the research team led by Ming Y. Lu at Harvard Medical School reported an interpretable weakly supervised deep learning method—Clustering-Constrained Attention Multiple Instance Learning (CLAM)—which improves the processing efficiency of large-scale WSI datasets, with performance superior to standard weakly supervised classification algorithms.

Although the application of weakly supervised learning in the field of pathology has made significant progress, the current stage still poses several challenges, such as noise processing of annotations, improvement of interpretability, and optimization of computational efficiency. Future research is expected to focus on developing more efficient weakly supervised frameworks, further reducing the reliance on annotated data, exploring the integration of self-supervised and weakly supervised approaches, and improving the interpretability and reliability of the model. Ultimately, the goal is to achieve clinical translation and transform diagnosis and treatment.

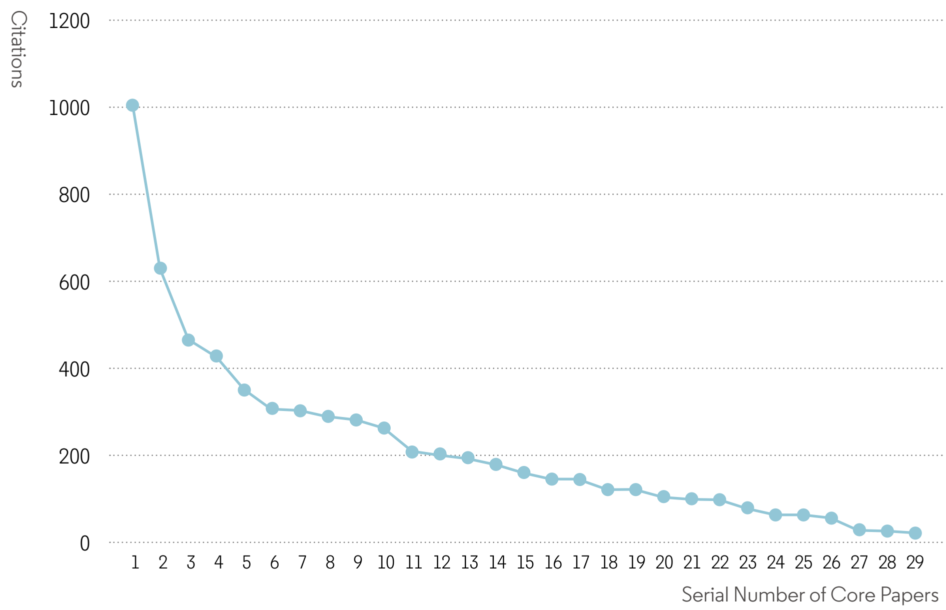
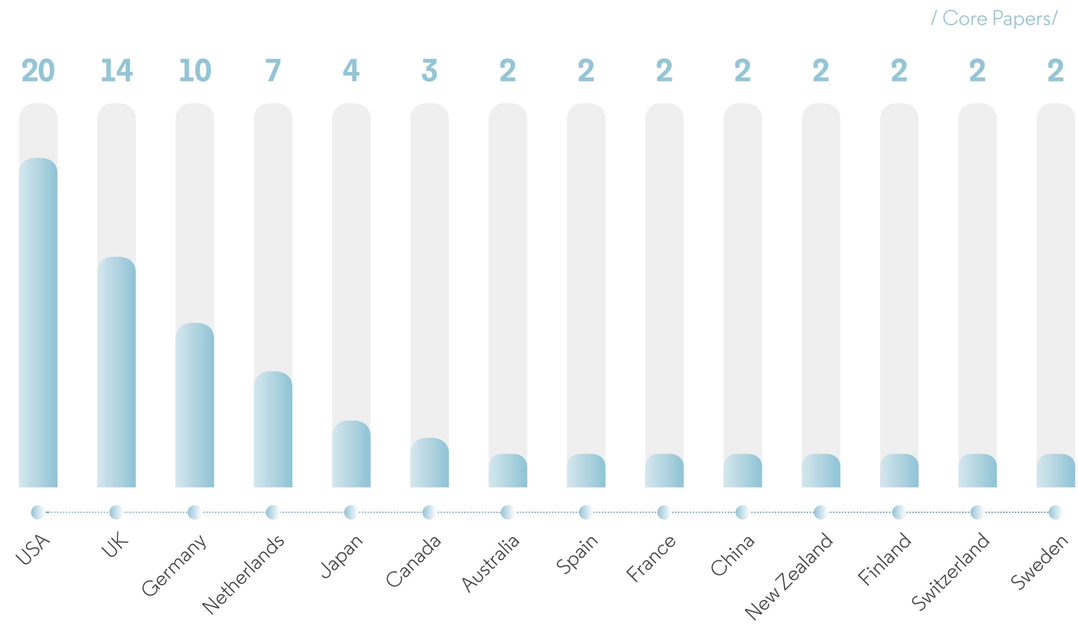


Figure 12: Citation frequency distribution curve of core papers in the Research Front "Weakly-supervised deep learning framework for whole-slide pathological images"

Among the top countries producing core papers in this hot front, the USA contributed nearly 70%, showing a significant advantage in the field. Most of the other contributing countries are in North America and Europe, with only Japan and China representing Asia. Among the top 10 producing institutions, five are based in the USA, and the remaining five are European installations, including three institutions in Germany, one in the UK, and one in the Netherlands. Europe and North America have already established a dominant position in this area.

Table 22: Top countries and institutions producing core papers in the Research Front "Weakly-supervised deep learning framework for whole-slide pathological images"

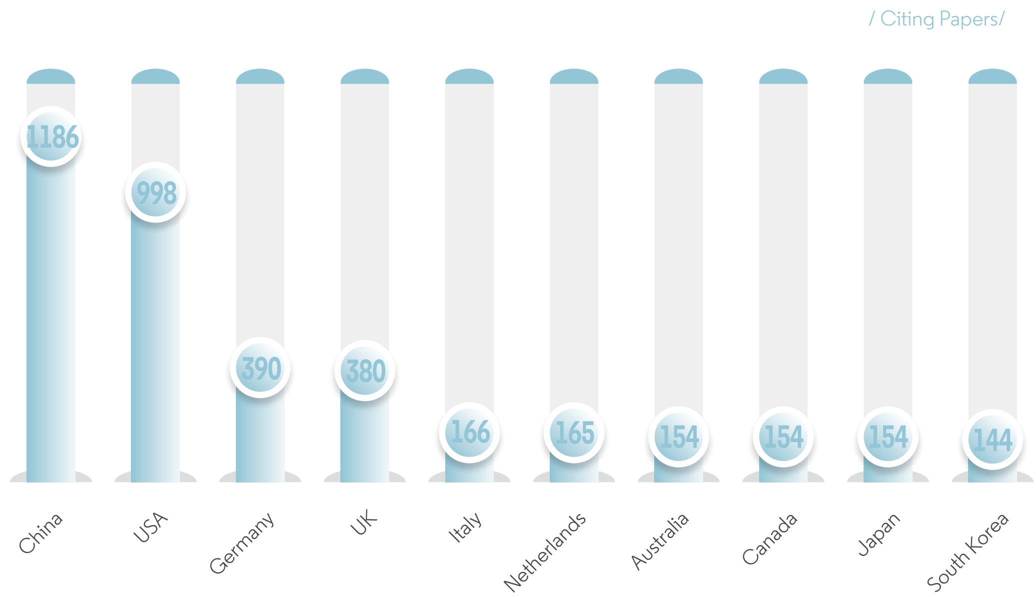
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	20	69.0%	1	RWTH Aachen University	Germany	8	27.6%
2	UK	14	48.3%	1	Helmholtz Association	Germany	8	27.6%
3	Germany	10	34.5%	3	Ruprecht-Karls—Universitaet Heidelberg	Germany	7	24.1%
4	Netherlands	7	24.1%	3	University of Leeds	UK	7	24.1%
5	Japan	4	13.8%	5	Maastricht University	Netherlands	5	17.2%
6	Canada	3	10.3%	5	Harvard University	USA	5	17.2%
7	Australia	2	6.9%	7	Dana Farber Cancer Center	USA	4	13.8%
7	Spain	2	6.9%	7	Broad Institute	USA	4	13.8%
7	France	2	6.9%	7	Massachusetts Institute of Technology (MIT)	USA	4	13.8%
7	China	2	6.9%	7	University of Chicago	USA	4	13.8%
7	New Zealand	2	6.9%					
7	Finland	2	6.9%					
7	Switzerland	2	6.9%					
7	Sweden	2	6.9%					



In terms of citing papers, China has the highest contribution rate, accounting for more than one-third. The USA follows closely, contributing nearly one-third as well. This indicates that China and the USA pay far more attention to this specialty area than other countries. The top institutions producing citing papers are mainly distributed in the USA, Germany, and China. Among them, Harvard University in the USA, Helmholtz Association in Germany, and the Chinese Academy of Sciences are representatives of the three countries respectively. And half of the top 10 institutions are based in China.

Table 23: Top countries and institutions producing citing papers in the Research Front "Weakly supervised deep learning framework for whole-slide pathological images"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1186	35.3%	1	Harvard University	USA	158	4.7%
2	USA	998	29.7%	2	Helmholtz Association	Germany	143	4.3%
3	Germany	390	11.6%	3	Chinese Academy of Sciences	China	130	3.9%
4	UK	380	11.3%	3	Ruprecht-Karls—Universitaet Heidelberg	Germany	130	3.9%
5	Italy	166	4.9%	5	Sun Yat Sen University	China	129	3.8%
6	Netherlands	165	4.9%	6	RWTHAachen University	Germany	99	2.9%
7	Australia	154	4.6%	8	Stanford University	USA	93	2.8%
7	Canada	154	4.6%	9	Fudan University	China	89	2.7%
7	Japan	154	4.6%	10	Shanghai Jiao Tong University	China	84	2.5%
10	South Korea	144	4.3%	10	Southern Medical University	China	75	2.2%



2. EMERGING RESEARCH FRONT

2.1 SUMMARY OF EMERGING RESEARCH FRONTS IN CLINICAL MEDICINE

The seven emerging Research Fronts selected in clinical medicine in 2025 mainly involve four aspects: “Immunotherapy mechanism of CAR-T cells”, “Treatment of tumor with new antigen vaccine”, “Clinical application of new modular surgical robot system (Hugo, etc.) in urology and gastrointestinal surgery”, and the front centering on “Application of artificial intelligence large language model ChatGPT in medical and health fields” which includes the application of AI large language model ChatGPT in radiology, ophthalmology, otolaryngology, nursing and other medical and health fields (see Table 24). The latter front, based on the criteria of comprehensive CPT index, Research Front development potential, and the judgment of scientific and technological information researchers, has been selected as the key focus for analysis.

Table 24: Emerging Research Fronts in clinical medicine

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Immunotherapy mechanism of CAR-T cells	7	155	2024.0
2	Treatment of tumor with new antigen vaccine	4	565	2023.8
3	**Systematic verification of reliability, applicability and boundary of artificial intelligence large language model ChatGPT in specialized medical scene**	**12**	**245**	**2023.8**
4	**Clinical application potential and limitations of artificial intelligence large language model ChatGPT in radiology field**	**17**	**492**	**2023.7**
5	Clinical application of new modular surgical robot system (Hugo, etc.) in urology and gastrointestinal surgery	11	220	2023.7
6	**Application of artificial intelligence large language model ChatGPT in classification, diagnosis, nursing and education of ophthalmic diseases**	**25**	**742**	**2023.6**
7	**Application, influence, challenge and integration path of artificial intelligence large language model ChatGPT in nursing education and medical health fields**	**8**	**180**	**2023.6**

2.2 KEY EMERGING RESEARCH FRONT – "Application of artificial intelligence large language model ChatGPT in medical and health fields"

ChatGPT is an advanced language model that uses deep learning technology to generate human-like responses to natural language inputs. It is a part of the GPT model family developed by OpenAI and is one of the largest publicly available language models to date. It can capture the nuances and complexities of human language, enabling it to generate appropriate and context-related responses across a wide range of prompts. Its potential application in healthcare ranges from identifying potential research topics to assisting professionals in clinical and laboratory diagnosis.

The research contents of this front include ChatGPT's analysis of the professional problems of otolaryngology; the support of ChatGPT to clinical decision-making of salivary gland endoscope and patient information; the evaluation and comparison of the accuracy and readability of otorhinolaryngology head and neck surgery information generated by ChatGPT-3.5 and -4; data mining of lung tumor CT reports using ChatGPT and GPT-4; the auxiliary function of GPT-4 in radiological and ophthalmic diagnosis; the role of ChatGPT in ophthalmology knowledge evaluation; the accuracy of comparing Google and ChatGPT in generating clinically relevant content in conditions such as appendicitis and cataract; and ChatGPT's impact on nursing education.

Interpretation of the front's literature had determined that the application of ChatGPT in otorhinolaryngology, head and neck surgery, imaging diagnosis, ophthalmology, and nursing is more regarded as a supplementary tool that enhances rather than replaces the knowledge and skills of clinicians. Specific uses include diagnosis, preoperative planning, intraoperative guidance, postoperative care, patient communication and education improvement, medical clinical teaching, and scientific research.

In the fields of imaging diagnosis, ophthalmology, and other specialties, the performance of ChatGPT is still insufficient and needs to transfer knowledge from common sense to the biomedical domain, also requiring further training to improve its performance in professional fields. In addition, ChatGPT has shown its advantages in patient education, which can not only provide patients with easy-to-understand health information and improve their health knowledge literacy, but also pcustomized answers according to specific questions.

In all, ChatGPT has brought new perspectives and tools to healthcare. It can help doctors more accurately predict the risk and outcome of diseases, provide patients with more personalized treatment plans, and optimize the diagnosis and documentation processes. However, we must also realize that ChatGPT is a double-edged sword, and its limitations and potential risks cannot be ignored. For example, when the generated content is used for commercial purposes, care must be taken not to infringe copyright and to comply with relevant laws and regulations.

2025
RESEARCH FRONTS

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 can be categorized into four thematic categories: technological innovation, microscopic mechanisms, medical applications and translational research, and macro-level interactions and health impacts.

Technological innovation provides a powerful engine for life-science research through revolutionary approaches, encompassing four technology-related Research Fronts: high-throughput single-cell technology, gene-editing technology, proteomics, and spatial transcriptomics. These four areas collectively form the core pillar technologies of life-science research in the 21st century and have been recognized as Research Fronts for many consecutive years. They offer essential tools for biological discoveries, continuously driving the field of life sciences toward greater precision and systematic advancement.

Work reflected in the micro-mechanism category primarily reveals the molecular basis of life processes, including one hot Research Front: “Protein lactylation”, which elucidates the novel signaling function of the classical metabolite lactate, providing a new molecular perspective for understanding physiological and pathological processes, such as immunity and tumors.

The specialty of medical applications and translational research aims to address major health challenges and advance the development of precision medicine, as embodied in three hot Research Fronts: 1) “Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine”, marking the first entry of Traditional Chinese Medicine research into Research Fronts; 2) “Immunogenicity mechanisms and immune response regulation of mRNA-LNP vaccines”, in which mRNA-LNP vaccine research directly contributes to infectious-disease prevention and control; and 3) “Tumor microbiome”, which offers, via microbial interactions, a novel perspective on diseases such as cancer.

Research in the category of macro-interaction and health impact primarily focuses on the complex interactions between organisms and their internal and external environments, along with the subsequent health effects. This specialty area includes two related Research Fronts: 1) “The causal mechanisms of host genetics and gut microbiota and their impact on metabolic and immune diseases”, which explores the causal mechanisms between intrinsic macro-interfaces and diseases; and 2) “Polystyrene microplastics induce reproductive toxicity in male mice”, continuing the trend of research on microplastic pollution consistently appearing among the hot fronts in the fields of ecology and environmental science over the past decade.

Current studies on emerging environmental pollutants such as polystyrene microplastics are evolving from the investigation of ecological and environmental phenomena to delving into the pathogenic mechanisms within organisms.

These directions collectively reflect the current development trends in life sciences, including multi-omics integration, technology-driven approaches, precise interventions, and a focus on interactions within complex systems.

Table 25: Top10 Research Fronts in biological sciences

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Protein lactylation	35	4865	2022.7
2	**Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine**	**13**	**1741**	**2022.4**
3	Constructing a Human Cell Atlas using High-Throughput Single-Cell Technology	4	1016	2022.0
4	Pioneering editing technologies and precise integration techniques for large DNA fragments	27	6192	2021.5
5	Immunogenicity mechanisms and immune response regulation of mRNA-LNP vaccines	6	1468	2021.5
6	High-throughput deep proteomics analysis based on DIA technology	7	1773	2021.4
7	Spatial transcriptomics technology and its application in high-resolution analysis of biological tissues	31	8795	2021.3
8	The causal mechanisms of host genetics and gut microbiota and their impact on metabolic and immune diseases	6	2557	2021.3
9	**Tumor microbiome**	**26**	**6943**	**2021.0**
10	Polystyrene microplastics induce reproductive toxicity in male mice	9	1838	2021.0

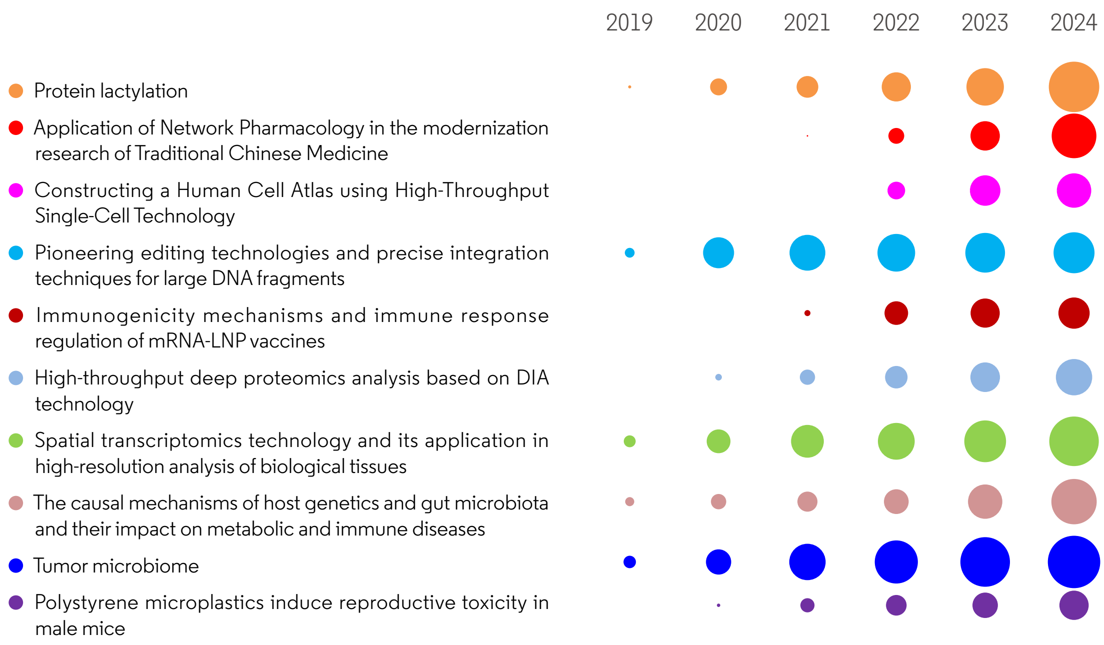


Figure 13: Citing papers for the Top 10 Research Fronts in biological sciences

1.2 KEY HOT RESEARCH FRONT – “Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine”

Network pharmacology is an emerging interdisciplinary field that integrates systems biology, polypharmacology, computational biology, and network science. This specialty constructs complex interaction networks between drugs, targets, and diseases to understand, at the system level, the holistic mechanisms by which drugs intervene in diseases.

The distinctive features of Traditional Chinese Medicine (TCM) lie in its holistic perspective, syndrome differentiation and treatment, and prescription-based medication. Past research methods, such as reductionism and trial-and-error, faced challenges that included the complexity of biological systems and intricate chemical compositions. Since its inception, network pharmacology has been regarded as the next-generation research model for TCM. This discipline plays a revolutionary role in the modernization of TCM research, as it perfectly aligns with the TCM’s core philosophical concepts—holism and systematic thinking—providing powerful theoretical tools and research paradigms for understanding the characteristics of traditional Chinese herbal formulas: specifically, multi-component, multi-target, and holistic regulation.

The 13 core papers on this front can be categorized into three research themes.

Theme 1 comprises five review articles that systematically outline the methodological framework of network pharmacology in TCM research. This theme emphasizes the core value of network pharmacology, in that the research provides a modern and scientific computational framework and expressive language for the holistic view of TCM, transforming it from an abstract philosophical concept into a quantifiable and simulatable research subject.

Theme 2 includes seven research articles, all focusing on the treatment of a certain complex disease with TCM compound prescriptions. By combining network pharmacology with molecular docking (and in vitro validation), these studies aim to elucidate the pharmacologically active components and molecular mechanisms underlying the therapeutic effects of the formulas on specific diseases. A significant challenge facing TCM is its unclear mechanism of action, often referred to as a black box.

Network pharmacology reveals how TCM compound prescriptions construct a component-target-pathway-disease network, visualizing and analyzing how drugs synergistically regulate multiple pathways through multi-target mechanisms, ultimately influencing disease phenotypes. This approach makes the mechanisms of TCM compound prescriptions clearer, more visual, and verifiable.

Theme 3 includes two recent research articles and one review article, focusing on the interdisciplinary integration of "AI + Network Pharmacology + Traditional Chinese Medicine" to advance the study of TCM from mechanism analysis to precise prediction.

In summary, the widespread application of network pharmacology in the field of TCM is driving the advancement of the discipline from an empirical medicine toward evidence-based medicine and precision medicine.

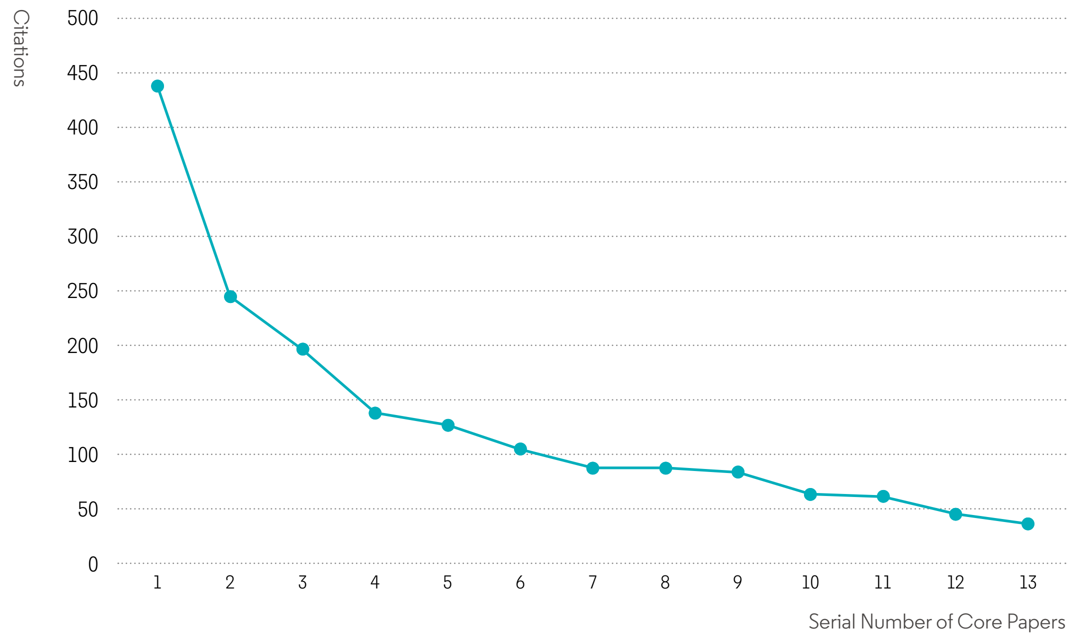


Figure 14: Citation frequency distribution curve of core papers in the Research Front "Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine"

In terms of the countries and institutions that produced core papers for this front, China contributed 76.9% of the foundational reports, holding a leading position in this field, followed by Pakistan, with two core papers. Among the top-producing institutions, three are in China: Tsinghua University, Zhejiang University, and Chengdu University of Traditional Chinese Medicine, each contributing two core papers. Additionally, Faisalabad Government College in Pakistan also contributed two (Table 26).

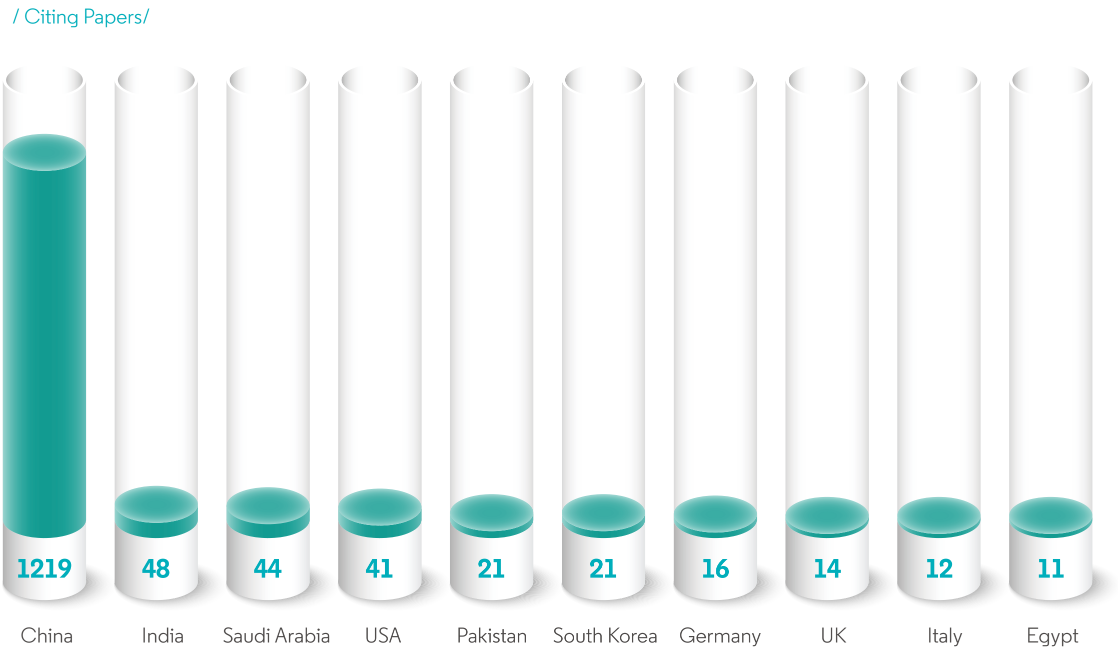
Table 26: Top countries and institutions producing core papers in the Research Front "Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	10	76.9%	1	Zhejiang University	China	2	15.4%
2	Pakistan	2	15.4%	1	Government College University Faisalabad	Pakistan	2	15.4%
3	Egypt	1	7.7%	1	Tsinghua University	China	2	15.4%
3	Hungary	1	7.7%	1	Chengdu University of Traditional Chinese Medicine	China	2	15.4%
3	UK	1	7.7%					
3	Ireland	1	7.7%					
3	Suriname	1	7.7%					
3	Germany	1	7.7%					
3	USA	1	7.7%					
3	Netherlands	1	7.7%					
3	Saudi Arabia	1	7.7%					

As for the distribution papers that cited the core literature (Table 27): China has published 1,219 citing papers, accounting for 89.1%, far exceeding other countries. The Top 10 institutions producing citing papers are all based in China, including eight universities of Traditional Chinese Medicine, as well as the Chinese Academy of Traditional Chinese Medicine and Southern Medical University.

Table 27: Top countries and institutions producing citing papers in the Research Front "Application of Network Pharmacology in the modernization research of Traditional Chinese Medicine"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1219	89.1%	1	Nanjing University Chinese Medicine	China	60	4.4%
2	India	48	3.5%	2	Zhejiang Chinese Medical University	China	59	4.3%
3	Saudi Arabia	44	3.2%	3	Chengdu University of Traditional Chinese Medicine	China	52	3.8%
4	USA	41	3.0%	4	Beijing University of Chinese Medicine	China	51	3.7%
5	Pakistan	21	1.5%	5	Shanghai University of Traditional Chinese Medicine	China	48	3.5%
6	South Korea	21	1.5%	6	Guangzhou University of Chinese Medicine	China	45	3.3%
7	Germany	16	1.2%	7	Shandong University of Traditional Chinese Medicine	China	40	2.9%
8	UK	14	1.0%	8	China Academy of Chinese Medical Sciences	China	34	2.5%
9	Italy	12	0.9%	9	Hunan University of Chinese Medicine	China	31	2.3%
10	Egypt	11	0.8%	10	Southern Medical University	China	30	2.2%



1.3 KEY HOT RESARCH FRONT – "Tumor microbiome"

The microbial community that exists in tumor tissue and constitutes the tumor microenvironment is called the tumor microbiome, including bacteria, fungi, viruses, and mycoplasma. Since the first cultivation of bacteria in human tumor tissues in the 1920s, increasing evidence suggests the presence of microbial communities in tumors. Due to the relatively low proportion of tumor microorganisms in the total mass of tumors and the strict control of pollution in the research process, the study of tumor microbiota has only recently been scaled up and become more systematic, emerging as one of the hottest research directions in the field of life sciences.

On May 29, 2020, the team of Ravid Strauss at the Weizmann Institute of Science in Israel published a paper titled "The human tumor microbiome is composed of tumor type specific intracellular bacteria" as the cover article in the journal *Science*. This is the most-cited core paper in this hot Research Front, with more than 1,030 citations at this writing. This study provides the first comprehensive analysis of the tumor microbiome, opening a new chapter in the study of this complex system.

This Research Front includes 26 core papers that collectively reveal the existence, composition, function, and clinical significance of the tumor microbiome. The research can be divided into four themes: 1) Discovery and characterization: This research has confirmed that there are specific bacterial and fungal communities in a variety of cancers (pancreatic, colorectal, breast, lung, melanoma, etc.; 2) Mechanism exploration: Work reflected in this theme has clarified that microorganisms promote tumor occurrence, progression, and metastasis by regulating host immunity (such as inducing IL-33, IL-1 β, Th17, Th2 responses), secreting toxins (such as BFT, Candidalysin), activating oncogenic pathways (such as Wnt/β - catenin, Notch), and causing DNA damage; 3) Clinical relevance: The discovery of specific microbial characteristics is closely related to cancer diagnosis, prognosis, classification, and response to immunotherapy, with great potential as biomarkers and therapeutic targets; and 4) Cross border interaction: Emphasizing the interaction among bacteria, fungi, and viruses (multi boundary microbial ecosystem interaction), and how they jointly shape the tumor microenvironment.

These studies have fundamentally changed our understanding of cancer, viewing tumors as a complex multi-boundary ecosystem. The work of understanding and manipulating this ecosystem has opened entirely new and highly promising avenues for cancer diagnosis, treatment, and prevention.

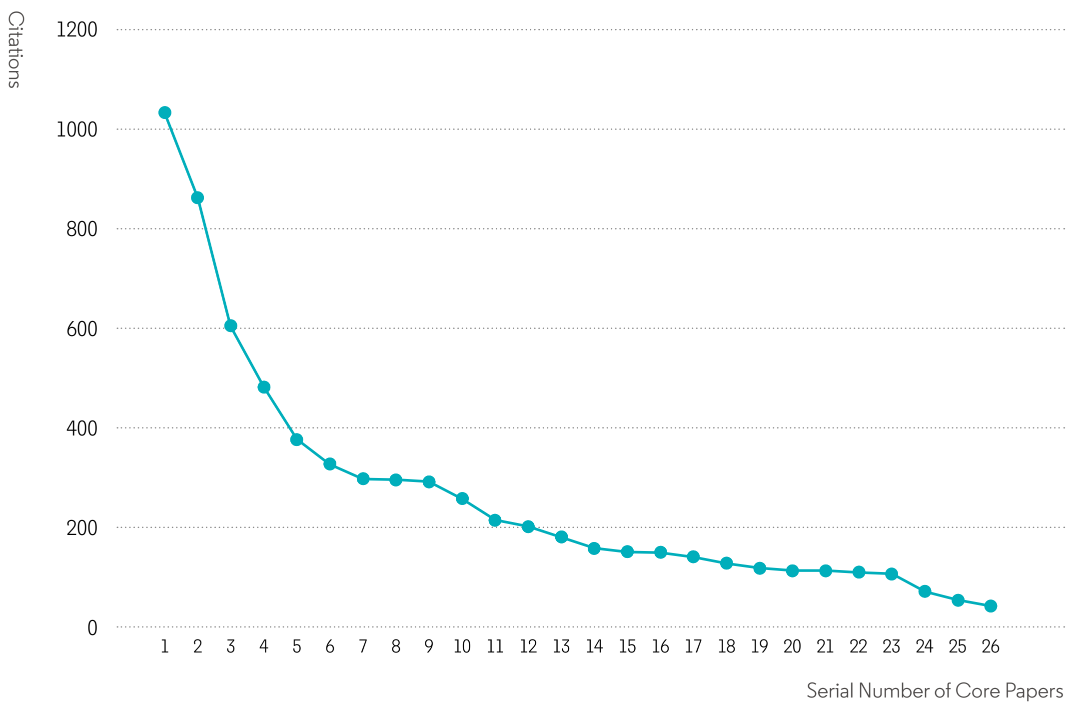
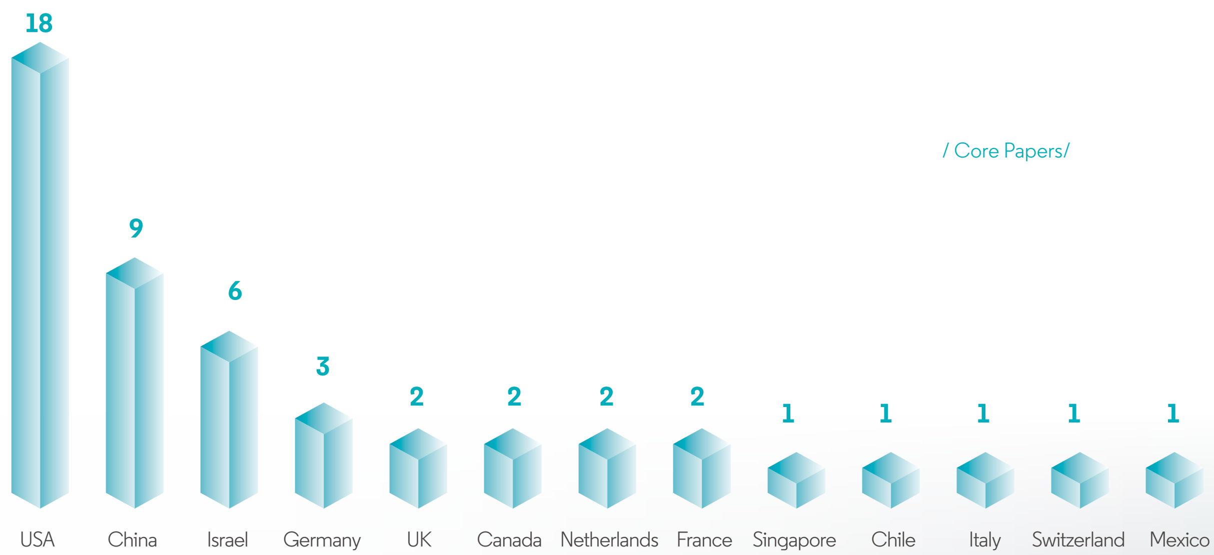


Figure 15: Citation frequency distribution curve of core papers in the Research Front "Tumor microbiome"

As for the distribution of core papers: the USA contributed 69.2% of the core, holding an absolute advantage in this area, while China ranked 2nd in terms of core paper output, accounting for 34.6%, with a certain gap compared to the USA. Among the top institutions in output (including nine tied), four are in Israel, three in the USA, and two in China, with Israel's Weizmann Institute of Science ranking 1st in core paper output.

Table 28: Top countries and institutions producing core papers in the Research Front "Tumor microbiome"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	18	69.2%	1	Weizmann Institute of Science	Israel	6	23.1%
2	China	9	34.6%	2	Utmd Anderson Cancer Center	USA	5	19.2%
3	Israel	6	23.1%	3	Chaim Sheba Medical Center	Israel	4	15.4%
4	Germany	3	11.5%	3	Zhejiang University	China	4	15.4%
5	UK	2	7.7%	3	Cornell University	USA	4	15.4%
5	Canada	2	7.7%	3	Tel Aviv University	Israel	4	15.4%
5	Netherlands	2	7.7%	7	The Open University of Israel	Israel	3	11.5%
5	France	2	7.7%	7	Sun Yat Sen University	China	3	11.5%
9	Singapore	1	3.8%	7	Johns Hopkins University	USA	3	11.5%
9	Chile	1	3.8%					
9	Italy	1	3.8%					
9	Switzerland	1	3.8%					
9	Mexico	1	3.8%					

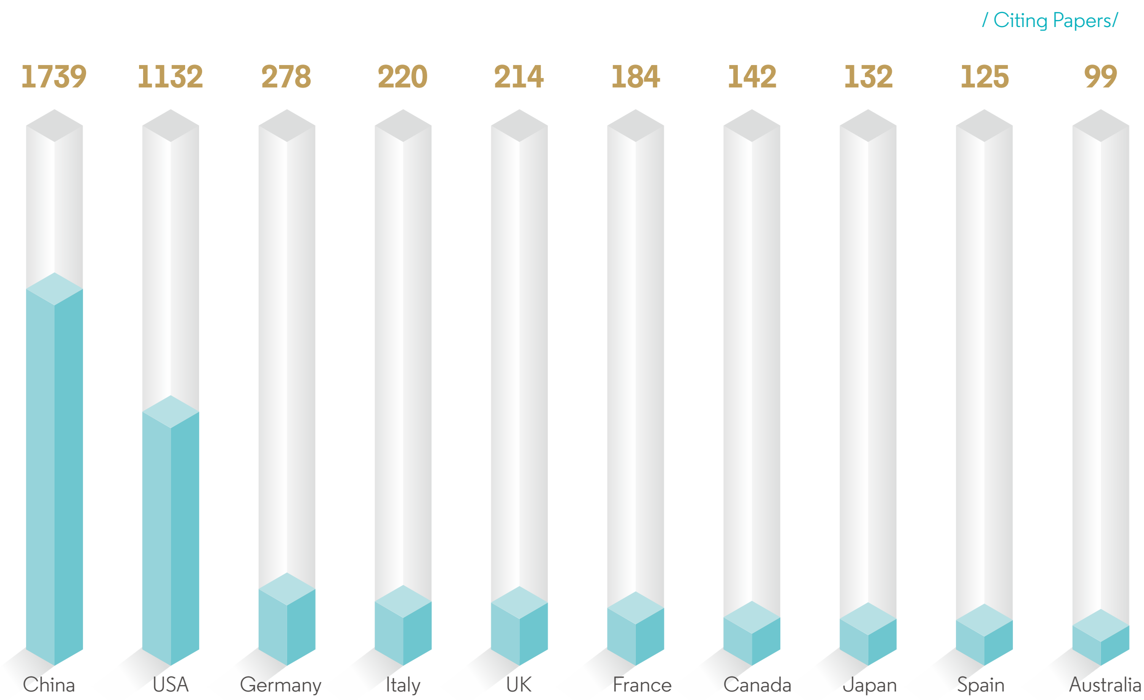


Analysis of the citing papers indicates that China has become the most active country in tracking this front, contributing more than 1,730 papers to date, followed by the USA, which produced more than 1,130 citing papers. Those figures demonstrate the keen and rapid extent to which the two countries are advancing knowledge in this front (Table 29).

Among the Top 10 institutions, six are in China, three in the USA, with the remainder in France. The Chinese Academy of Sciences and Shanghai Jiao Tong University rank 1st and 2nd respectively, and Harvard University and the MD Anderson Cancer Center of the University of Texas are tied for 3rd place.

Table 29: Top countries and institutions producing citing papers in the Research Front "Tumor microbiome"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1739	43.1%	1	Chinese Academy of Sciences	China	157	3.9%
2	USA	1132	28.0%	2	Shanghai Jiao Tong University	China	128	3.2%
3	Germany	278	6.9%	3	Harvard University	USA	116	2.9%
4	Italy	220	5.4%	3	UTMD Anderson Cancer Center	USA	116	2.9%
5	UK	214	5.3%	5	National Institute of Health and Medical Research (INSERM)	France	107	2.7%
6	France	184	4.6%	5	Zhejiang University	China	107	2.7%
7	Canada	142	3.5%	7	Chinese Academy of Medical Sciences - Peking Union Medical College	China	104	2.6%
8	Japan	132	3.3%	8	Sun Yat Sen University	China	102	2.5%
9	Spain	125	3.1%	9	Sichuan University	China	81	2.0%
10	Australia	99	2.5%	10	National Institutes of Health (NIH)	USA	77	1.9%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN BIOLOGICAL SCIENCES

Four specialty areas in biological sciences have been identified as emerging fronts, with the main research topics including “New breakthroughs in AI-driven structural prediction and design of biomolecular complexes”, “Construction of an AI-driven multidimensional genomic variant functional prediction and pathogenicity assessment system”, “The mechanism of 7-dehydrocholesterol in Ferroptosis”, and “Species-specific temporal mechanisms of metabolic and epigenetic co-regulation in neuronal development”. Based on the comprehensive CPT indicators for evaluating Research Fronts (please refer to the methodology section for details), the development potential of these fronts, and the assessment of science and technology intelligence researchers, the front “New breakthroughs in AI-driven structural prediction and design of biomolecular complexes” was ultimately selected for closer examination.

Table 30: Emerging Research Fronts in biological sciences

Rank	Emerging Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	**New breakthroughs in AI-driven structural prediction and design of biomolecular complexes**	**3**	**1006**	**2024.0**
2	Construction of an AI-driven multidimensional genomic variant functional prediction and pathogenicity assessment system	2	281	2024.0
3	The mechanism of 7-dehydrocholesterol in Ferroptosis	4	192	2024.0
4	Species-specific temporal mechanisms of metabolic and epigenetic co-regulation in neuronal development	5	226	2023.6

2.2 KEY EMERGING RESARCH FRONT – “New breakthroughs in AI-driven structural prediction and design of biomolecular complexes”

In 2020, DeepMind, a Google subsidiary, launched AlphaFold, an AI-powered tool for predicting protein structures. In July 2021, the DeepMind team introduced AlphaFold2, which can accurately predict three-dimensional protein structures from amino acid sequences. The emergence of AlphaFold2 sparked a revolution in protein structure modeling and interaction studies, opening vast possibilities for protein modeling and design applications, and demonstrating AI’s immense potential in structural prediction. On October 9, 2024, DeepMind researchers Demis Hassabis and John Jumper shared the 2024 Nobel Prize in Chemistry along with David Baker, a pioneer in protein design at the University of Washington, for their groundbreaking contributions to protein structure prediction and protein design.

This Research Front features three core papers. The first concerns AlphaFold3, the comprehensive upgrade of Google DeepMind’s AlphaFold2 developed by Hassabis and Jumper in 2024. The second paper highlights new advancements by Baker’s team at the University of Washington, including the all-atom prediction model RoseTTAFold All-Atom (RFAA) with functionalities similar to AlphaFold3, along with an unprecedented design tool called RFdiffusionAA. Both AlphaFold3 and RFAA have transcended their original focus on proteins, now expanding their capabilities to predict and design biological complexes such as nucleic acids and small molecules, achieving accuracy surpassing many specialized tools.

In the third core paper, researchers from the Free University of Berlin reported their development of a novel protein-ligand structure prediction tool (Umol), demonstrating the accuracy of deep learning methods in predicting protein-ligand complex structures without structural information. This breakthrough provides new perspectives for predicting drug-target interactions and understanding protein-ligand interactions.

These three papers represent the most groundbreaking advancements in biomolecular structure prediction and design in 2024, collectively ushering the field from single-protein structure prediction to a new era of full-atom biomolecular system modeling. These research achievements mark significant progress in AI applications for biomolecular structure prediction and design. The developed tools will greatly accelerate the development of new drug discovery, synthetic biology, and materials science, shifting the paradigm from large-scale screening to rational design as the mainstream approach. Looking ahead, it is certain that AI will advance toward dynamic full-atom simulations and precise functional design, ultimately bringing about fundamental transformations in fields such as drug discovery and synthetic biology.

2025
RESEARCH FRONTS

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 2025 spotlight specialty areas in synthetic chemistry, materials recovery and recycling, lithium batteries, and energy materials. In the field of synthetic chemistry, four Research Fronts have been selected, covering medicinal chemistry ("Synthesis of bioisosteres of the phenyl ring"), photochemistry ("Covalent organic frameworks for photocatalytic hydrogen peroxide production"), electrochemistry ("CO_2 electroreduction to multicarbon products"), and biochemistry ("Directed evolution and design of PET hydrolases").

Two fronts represent the field of materials recovery and recycling, focusing respectively on waste lithium-ion batteries and waste polyolefin plastics. Two hot fronts in the field of lithium batteries are highlighted, examining single-crystalline Ni-rich cathodes and halide solid electrolytes. In the area of energy materials, two fronts have been identified, focusing on thermoelectric materials and energy storage materials.

Table 31: Top10 Research Fronts in chemistry and materials science

Rank	Hot Research Fronts	Core papers	Citations	Mean Year of Core Papers
1	Synthesis of bioisosteres of the phenyl ring	40	2738	2023.1
2	High-performance thermoelectric materials	21	2889	2022.9
3	Covalent organic frameworks for photocatalytic hydrogen peroxide production	34	5149	2022.5
4	Recycling spent lithium-ion battery cathode materials	33	8121	2021.8
5	**Chemical recycling and upcycling of waste polyolefin plastics**	**42**	**8845**	**2021.5**
6	Single-crystalline Ni-rich cathodes for Li-ion batteries	19	4442	2021.4
7	Polymers dielectric for high-temperature capacitive energy storage	35	6667	2021.3
8	**Halide solid electrolytes for all-solid-state batteries**	**26**	**5089**	**2021.3**
9	CO_2 electroreduction to multicarbon products	14	3549	2021.3
10	Directed evolution and design of PET hydrolases	24	4862	2021.2

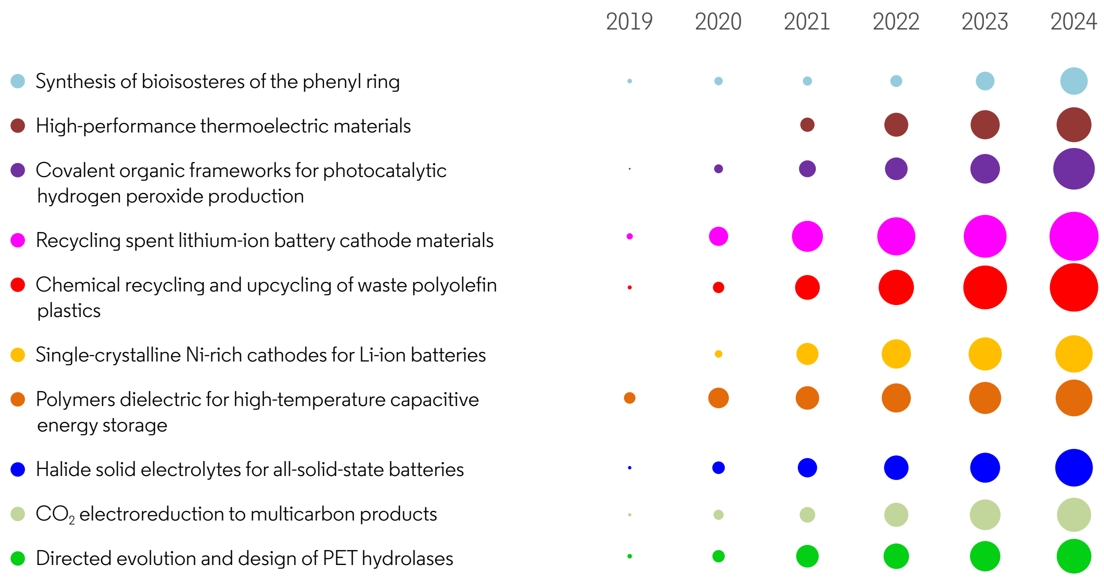


Figure 16: Citing papers of the Top 10 Research Fronts in chemistry and materials science

1.2 KEY HOT RESEARCH FRONT – "Chemical recycling and upcycling of waste polyolefin plastics"

Plastic pollution is one of the most pressing environmental challenges facing the world today, accounting for more than $1.5 trillion in health and environmental costs each year. Recycling is an important approach to addressing plastic pollution, and current recycling strategies for plastics are broadly classified as mechanical and chemical. Mechanical recycling uses physical methods (such as crushing and melting) to convert waste plastics into secondary products or materials. This approach is simple, easy to implement, and low cost, but it has limitations—particularly that recycled materials often exhibit inferior properties.

In contrast, chemical recycling is more complex but potentially more promising. This approach comprises two pathways: closed loop recycling and open-loop recycling (upcycling). Closed-loop recycling depolymerizes waste plastics into their constituent monomers, which can be repolymerized to produce the same plastics with near-virgin properties. Upcycling uses waste plastics as a feedstocks to synthesize value-added chemicals and materials.

Polyolefins are the highest-volume plastics, with polyethylene and polypropylene accounting for 26% and 19% of global plastic production, respectively, as of 2022. Because C–C bond cleavage is endothermic and thermodynamically unfavorable at low temperatures, chemical recycling of waste polyolefins is particularly challenging.

The 42 highly cited papers constituting the core of this Research Front focus on chemical recycling of polyolefins and report on the development of a variety of methods,—including catalytic pyrolysis, catalytic hydrogenolysis, tandem hydrogenolysis/aromatization, and tandem cracking/alkylation—and the corresponding catalysts. The four most-cited publications are all review articles that summarize various chemical recycling technologies. The fifth-ranked publication is coauthored by researchers at the University of California, Santa Barbara, and other US-based institutions. In this paper, researchers coupled exothermic hydrogenolysis with endothermic aromatization, rendering the overall transformation of polyethylene upcycling to long-chain alkylaromatics thermodynamically accessible at the moderate reaction temperature of 280° C.

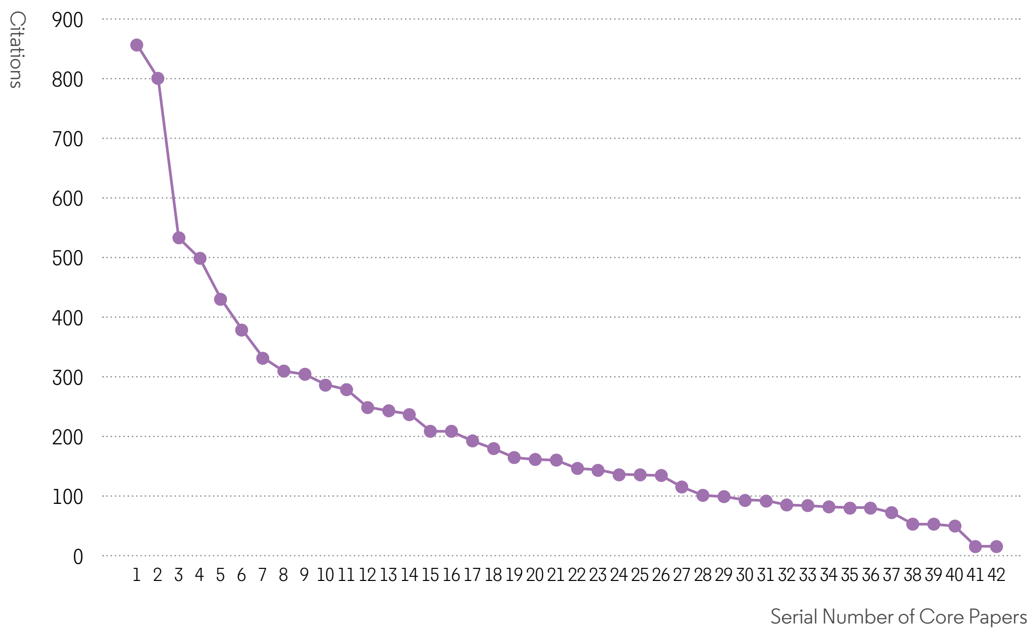
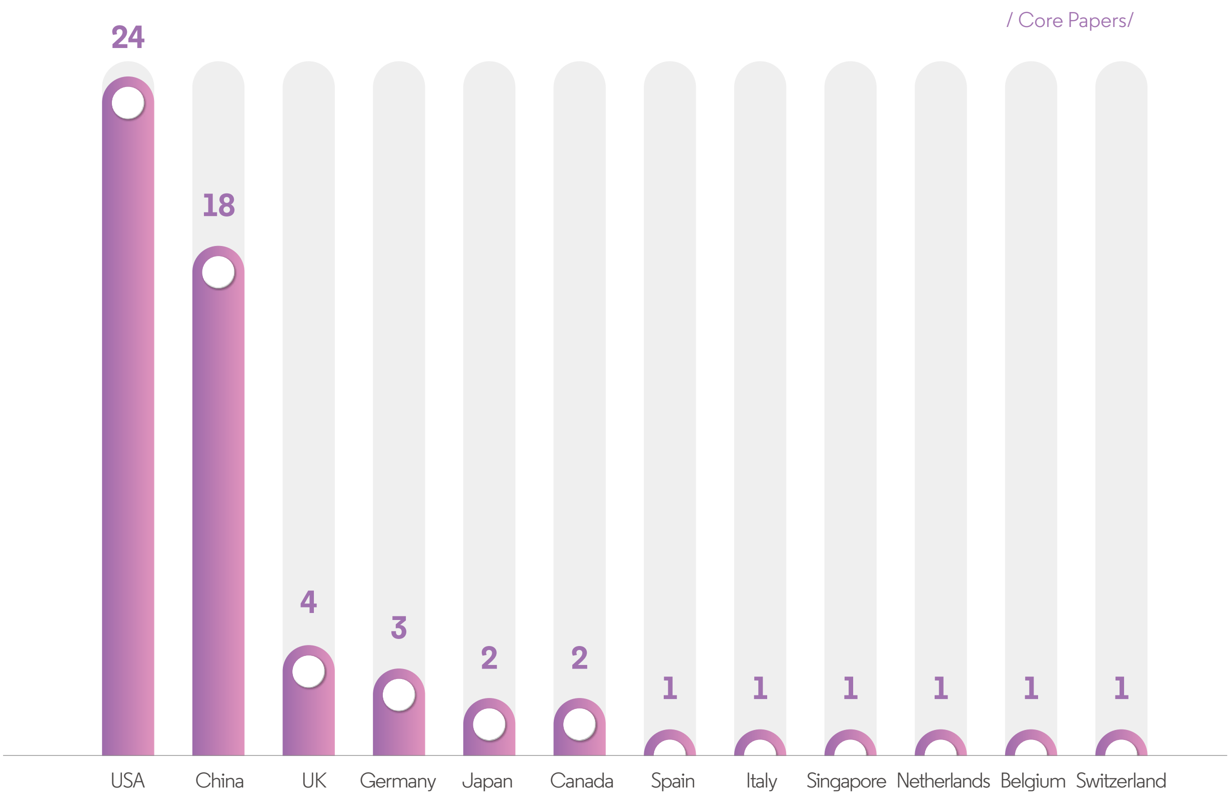


Figure17: Citation frequency distribution curve of core papers in the Research Front "Chemical recycling and upcycling of waste polyolefin plastics"

As shown in Table 32, the 42 core papers in this Research Front come from 12 countries and reflect a considerable degree of international co-authorship, demonstrating the heightened level of global concern about the recycling of waste polyolefins. The USA has contributed 24 papers and China 18, significantly more than any other country on the list. Among the Top 10 institutions producing core papers, the Chinese Academy of Sciences accounts for seven papers, while several US-based institutions, including Cornell University, Argonne National Laboratory, and the National Renewable Energy Laboratory, also make the list.

Table 32: Top countries and institutions producing core papers in the Research Front "Chemical recycling and upcycling of waste polyolefin plastics"

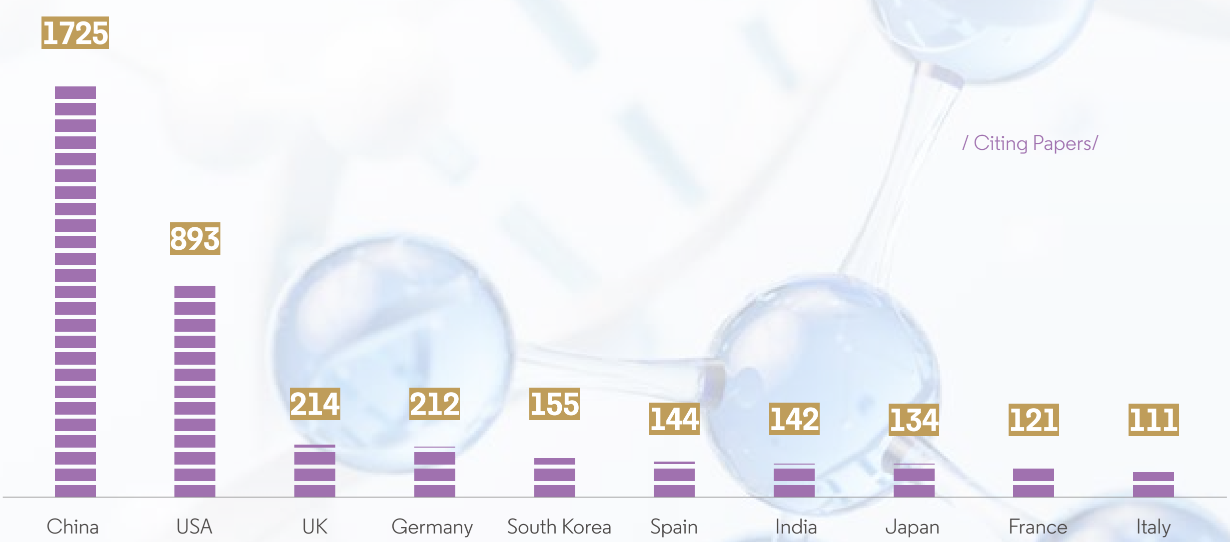
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	24	57.1%	1	Chinese Academy of Sciences	China	7	16.7%
2	China	18	42.9%	2	Cornell University	USA	5	11.9%
3	UK	4	9.5%	3	Argonne National Laboratory	USA	4	9.5%
4	Germany	3	7.1%	3	National Renewable Energy Laboratory	USA	4	9.5%
5	Japan	2	4.8%	5	University of California, Santa Barbara	USA	3	7.1%
5	Canada	2	4.8%	5	University of Wisconsin Madison	USA	3	7.1%
7	Spain	1	2.4%	5	University of Illinois Urbana-Champaign	USA	3	7.1%
7	Italy	1	2.4%	5	University of Delaware	USA	3	7.1%
7	Singapore	1	2.4%	5	Massachusetts Institute of Technology	USA	3	7.1%
7	Netherlands	1	2.4%	5	Colorado State University	USA	3	7.1%
7	Belgium	1	2.4%					
7	Switzerland	1	2.4%					



As Table 33 shows, China and the USA respectively ranked 1st and 2nd in producing citing papers, far ahead of other countries on the list. Eight Chinese institutions, including the Chinese Academy of Sciences, ranked among the Top 10 citing institutions, reflecting China's strong focus and sustained engagement in this research area.

Table 33: Top countries and institutions producing citing papers in the Research Front "Chemical recycling and upcycling of waste polyolefin plastics"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1725	44.7%	1	Chinese Academy of Sciences	China	395	10.2%
2	USA	893	23.2%	2	Zhejiang University	China	111	2.9%
3	UK	214	5.5%	3	Sichuan University	China	107	2.8%
4	Germany	212	5.5%	3	University of Science and Technology of China	China	107	2.8%
5	South Korea	155	4.0%	5	National Center for Scientific Research of France (CNRS)	France	91	2.4%
6	Spain	144	3.7%	6	Peking University	China	72	1.9%
7	India	142	3.7%	7	Tsinghua University	China	66	1.7%
8	Japan	134	3.5%	8	National Renewable Energy Laboratory	USA	64	1.7%
9	France	121	3.1%	9	Shanghai Jiao Tong University	China	61	1.6%
10	Italy	111	2.9%	10	East China University of Science and Technology	China	58	1.5%



1.3 KEY HOT RESARCH FRONT – "Halide solid electrolytes for all-solid-state batteries"

All-solid-state batteries using solid-state electrolytes (SSEs) are considered a promising power source for electric vehicles because they can achieve higher energy density and improved safety by eliminating the flammable liquid electrolytes used in conventional lithiumion batteries. SSEs are key components of all-solid-state batteries, as battery performance strongly depends on their properties. SSEs are mainly classified into three categories: polymer, inorganic, and hybrid (polymer + inorganic). Inorganic SSEs can be further subdivided into oxides, sulfides, halides, borohydrides, and other types. Among these, oxide-, sulfide-, and polymer-based SSEs are regarded as the most promising candidates for all-solid-state batteries, while borohydride- and halide-based SSEs have also made breakthrough progress in recent years.

Because of their high room-temperature ionic conductivity and good compatibility with oxide cathodes, halide-based SSEs have regained interest for application in all-solid-state batteries. Of the 26 highly cited papers that form the core of this Research Front, most report chloride-based SSEs, with several studies on oxychlorides and bromides. The most-cited core paper was coauthored by researchers at Western University (Canada), China Automotive Battery Research Institute Co. Ltd (China), and other institutions in the two countries. In this paper, researchers report a rationally designed halide-based Li_3InCl_6 SSE with a high ionic conductivity of 1.49×10^{-3} S cm^{-1}. The material is stable towards oxide cathode materials and highly stable in ambient air.

The second-most-cited core paper results from a collaboration between Peking University (China) and the University of Maryland, College Park (USA). The researchers used first principles computation to investigate the Li-ion diffusion, electrochemical stability, and interface stability of chloride and bromide materials, elucidating the origin of their high ionic conductivities and good electrochemical stability.

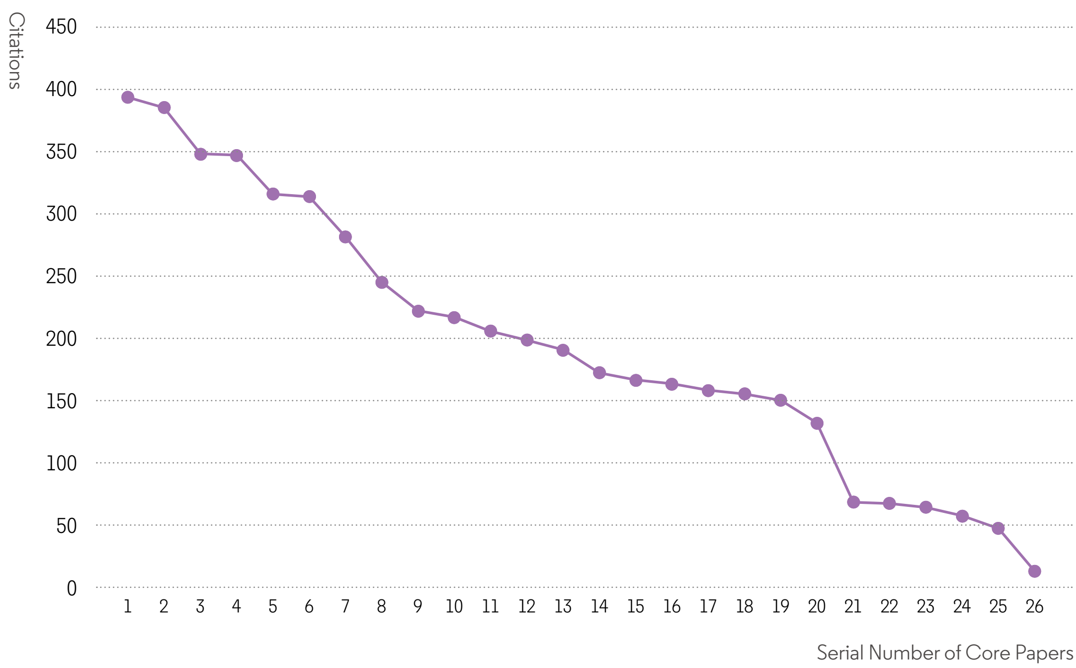
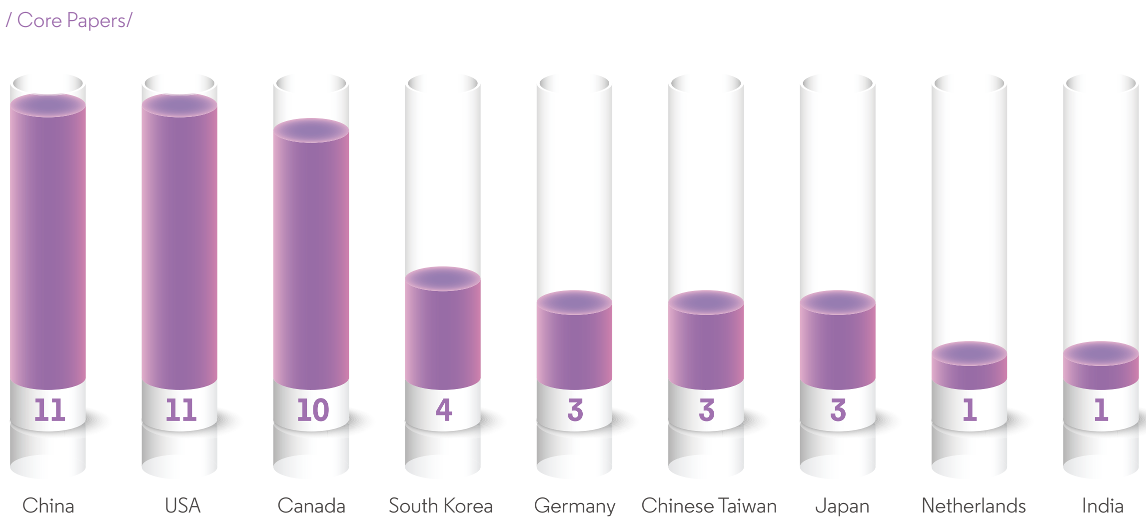


Figure18: Citation frequency distribution curve of core papers in the Research Front "Halide solid electrolytes for all-solid-state batteries"

As shown in Table 34, the 26 core papers in this front represent nine countries/regions. China and the USA each contributed 11 papers, tying for first place. Canada follows closely with 10 papers. In the Top 10 institutions producing core papers, Western University (Canada) leads with seven papers, followed by the Chinese Academy of Sciences, Oak Ridge National Laboratory (USA), and the University of Saskatchewan (Canada) each contributing five papers. The China Automotive Battery Research Institute Co. Ltd and Canada-based GLABAT Solid-State Battery Inc. also make the list.

Table 34: Top countries/regions and institutions producing core papers in the Research Front "Halide solid electrolytes for all-solid-state batteries"

Country Ranking	Country/ region	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country/ region	Core Papers	Proportion
1	China	11	42.3%	1	Western University (University of Western Ontario)	Canada	7	26.9%
1	USA	11	42.3%	2	Chinese Academy of Sciences	China	5	19.2%
3	Canada	10	38.5%	2	Oak Ridge National Laboratory	USA	5	19.2%
4	South Korea	4	15.4%	2	University of Saskatchewan	Canada	5	19.2%
5	Germany	3	11.5%	5	Yonsei University	South Korea	4	15.4%
5	Chinese Taiwan	3	11.5%	6	University of Science and Technology of China	China	3	11.5%
5	Japan	3	11.5%	6	University of Waterloo	Canada	3	11.5%
8	Netherlands	1	3.8%	6	University of Maryland College Park	USA	3	11.5%
8	India	1	3.8%	6	China Automotive Battery Research Institute Co. Ltd	China	3	11.5%
				6	GLABAT Solid-State Battery Inc.	Canada	3	11.5%
				6	National Synchrotron Radiation Research Center	Chinese Taiwan	3	11.5%

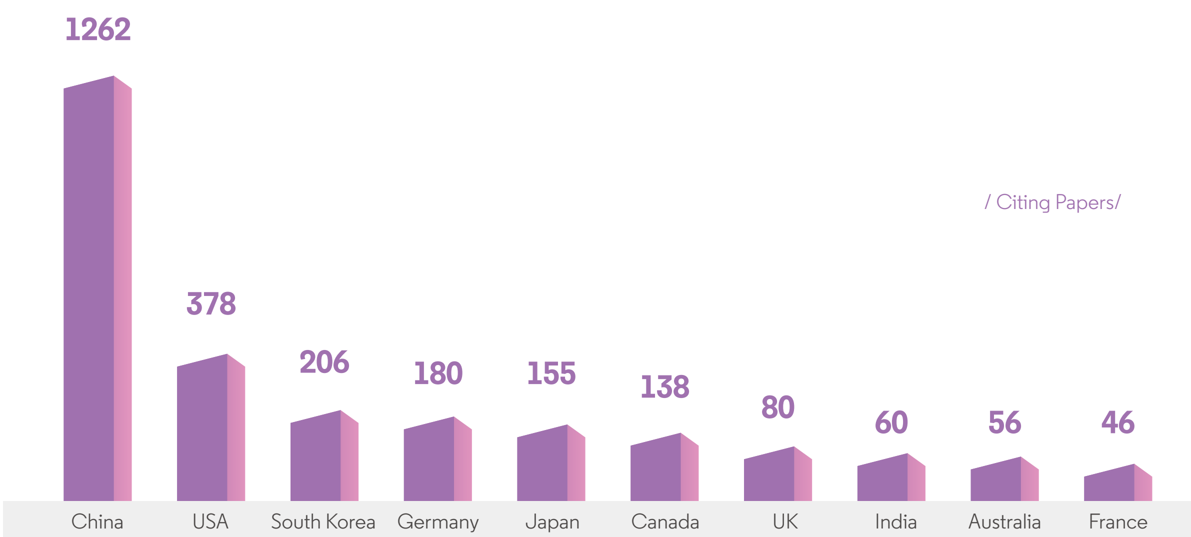


As shown in Table 35, China significantly surpasses other countries in total output of citing papers, reflecting the nation's strong focus on this research area. The USA and South Korea follow at 2nd and 3rd place, respectively.

Among the Top 10 institutions producing citing papers, institutions from China, Canada, Germany, and the USA are on the list, with the Chinese Academy of Sciences ranking 1st in terms of publication volume.

Table 35: Top countries and institutions producing citing papers in the Research Front "Halide solid electrolytes for all-solid-state batteries"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1262	59.3%	1	Chinese Academy of Sciences	China	226	10.6%
2	USA	378	17.8%	2	Tsinghua University	China	90	4.2%
3	South Korea	206	9.7%	3	Western University (University of Western Ontario)	Canada	88	4.1%
4	Germany	180	8.5%	4	Helmholtz Association	Germany	82	3.9%
5	Japan	155	7.3%	5	Shanghai Jiao Tong University	China	75	3.5%
6	Canada	138	6.5%	6	Huazhong University of Science & Technology	China	73	3.4%
7	UK	80	3.8%	7	University of Science and Technology of China	China	67	3.1%
8	India	60	2.8%	8	Justus Liebig University Giessen	Germany	56	2.6%
9	Australia	56	2.6%	9	Oak Ridge National Laboratory	USA	52	2.4%
10	France	46	2.2%	10	Karlsruhe Institute of Technology	Germany	47	2.2%
				10	Peking University	China	47	2.2%
				10	Zhejiang University	China	47	2.2%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN CHEMISTRY AND MATERIALS SCIENCE

In the field of chemistry and materials science, one research topic has been selected as an Emerging Research Front: "Strategies for Enhancing Conversion Efficiency and Stability of Inverted Perovskite Solar Cells".

Table 36: Emerging Research Front in chemistry and materials science

Rank	Emerging Research Front	Core Papers	Citations	Mean Year of Core Papers
1	Strategies for Enhancing Conversion Efficiency and Stability of Inverted Perovskite Solar Cells	4	461	2024.0

2.2 KEY EMERGING RESEARCH FRONT – "Strategies for Enhancing Conversion Efficiency and Stability of Inverted Perovskite Solar Cells"

Perovskite solar cells (PSCs) possess excellent photoelectric conversion efficiency as well as the advantage of low-temperature solution processability, distinguishing them as a core development direction for next-generation photovoltaic technologies. Inverted PSCs adopt a vertically stacked positive-intrinsic-negative (p-i-n) structure ("hole transport layer – perovskite light-absorbing layer – electron transport layer"), in which incident light first passes through the hole transport layer. Compared with conventional n-i-p structured PSC's ("electron transport layer – perovskite light-absorbing layer – hole transport layer"), where incident light first passes through the electron transport layer, the inverted structure exhibits significant advantages in interface stability, process compatibility, and industrial adaptability—providing strong support for the large-scale production and commercial application of inverted PSCs.

Currently, research in this field mainly focuses on improving conversion efficiency and interface stability, and the core papers in this Emerging Research Front propose innovative strategies for addressing those key issues.

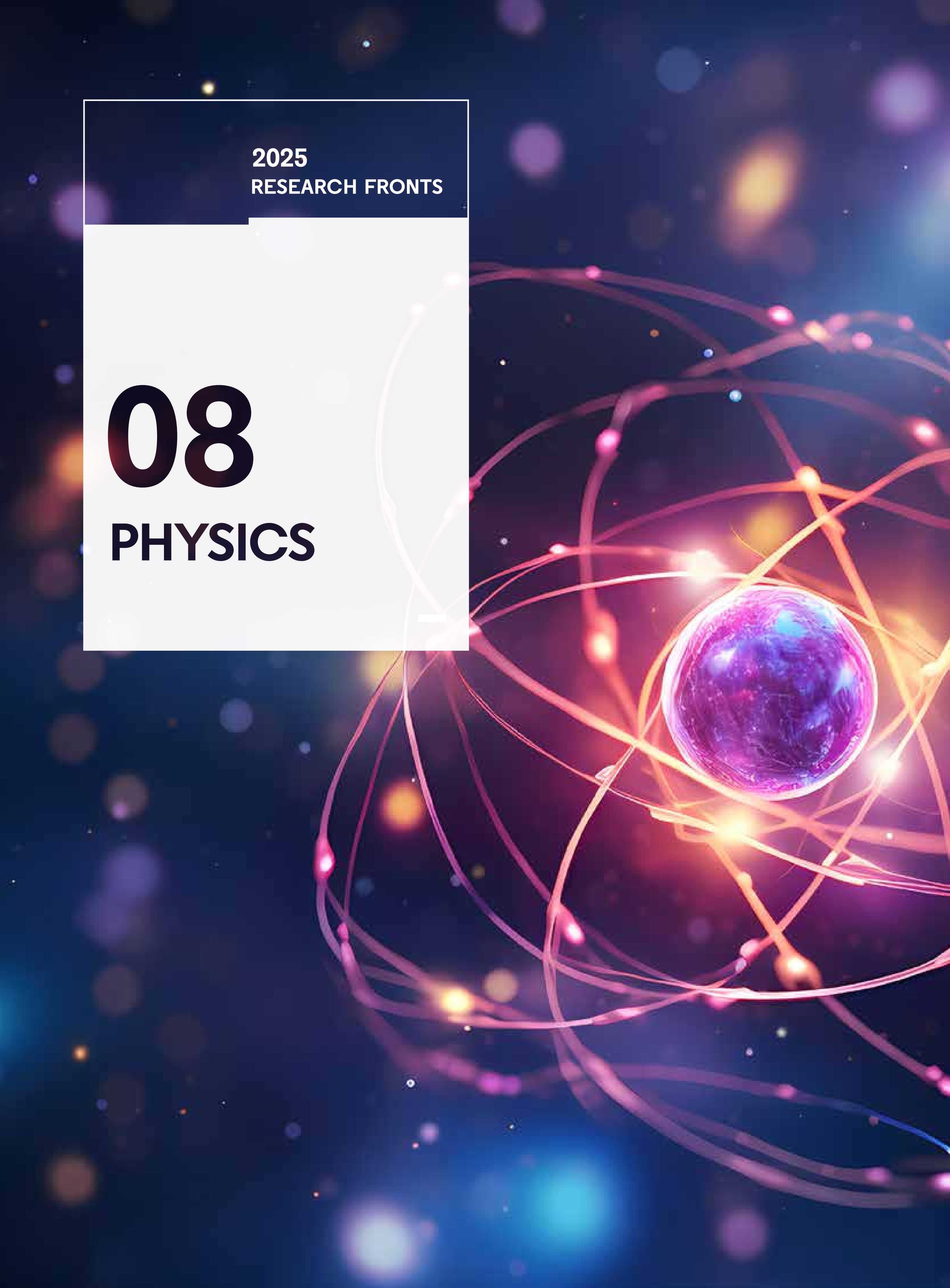
A collaboration between institutions including Northwestern University (USA) and ShanghaiTech University (China) designed a planar ligand capable of passivating two neighboring lead (II) ion (Pb^{2+}) defect simultaneously. This strategy effectively reduced non-radiative recombination of carriers, achieving certified quasi-steady-state efficiencies of up to 26.15% (for 0.05 cm^2 devices) and 24.74% (for 1.04 cm^2 devices), while maintaining 95% of the initial performance after 1,200 hours of continuous 1 sun maximum power point operation at 65 degrees C.

Researchers from Huazhong University of Science and Technology (China) and Sungkyunkwan University (South Korea) collaborated to propose a hybrid strategy of co-assembling the popular self-assembled molecule phosphonic acid (Me-4PACz) with multiple aromatic carboxylic acid to improve the heterojunction interface. This significantly optimized interface contact and carrier extraction capability, enabling a record-certified steady-state efficiency of 26.54% and an efficiency of 22.74% in 11.1 cm^2 mini-modules.

A team at Zhejiang University (China) and Westlake University (China) proposed a peri-fused polyaromatic core structure without heteroatom substitution from the perspective of molecular design, which enabled a device efficiency of 26.1%.

With continuous breakthroughs in interface passivation strategies and novel transport materials, inverted PSCs are expected to further approach the theoretical efficiency limit while maintaining their inherent stability and process advantages—ultimately driving the large-scale commercial application of next-generation photovoltaic technologies.

08
PHYSICS



1. HOT RESEARCH FRONTS

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, optics, quantum physics, theoretical physics, and semiconductor physics. Four Research Fronts pertain to condensed matter physics. Research on superconducting materials continues to be highly active, while hydrogen-rich compounds register as a hot Research Front for the fifth consecutive year, and the superconducting diode effect has emerged as a new hot front. Studies on ferroelectricity have also sparked widespread interest. Ferroelectricity in HfO_2 thin films and 2D van der Waals materials have been selected as hot fronts for the first time.

Two hot Research Fronts concern optics. Novel nonlinear optical materials have been selected again after many years, while petawatt-class lasers and their applications have newly emerged. In quantum physics, Twin-field quantum key distribution has now been recognized as a hot front for three consecutive years, and quantum simulation of lattice gauge theories has newly appeared. In theoretical physics, non-invertible symmetries have attracted much attention. In semiconductor physics, gallium oxide power devices have registered as a hot front for two consecutive years.

Table 37: Top10 Research Fronts in physics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Non-invertible symmetries	48	2815	2022.9
2	**Superconducting diode effect**	**22**	**2076**	**2022.5**
3	High-temperature superconductivity in hydrogen-rich compounds under high pressure	35	5508	2022.0
4	Ga_2O_3 power devices	17	2006	2021.8
5	Ferroelectricity in HfO_2 thin films	12	1979	2021.8
6	New nonlinear optical materials	50	6650	2021.7
7	Ferroelectricity in 2D van der Waals materials	13	2308	2021.7
8	Quantum simulation of lattice gauge theories	18	1980	2021.7
9	**Petawatt class lasers and their applications**	**10**	**2078**	**2021.4**
10	Twin-field quantum key distribution	32	5393	2021.3

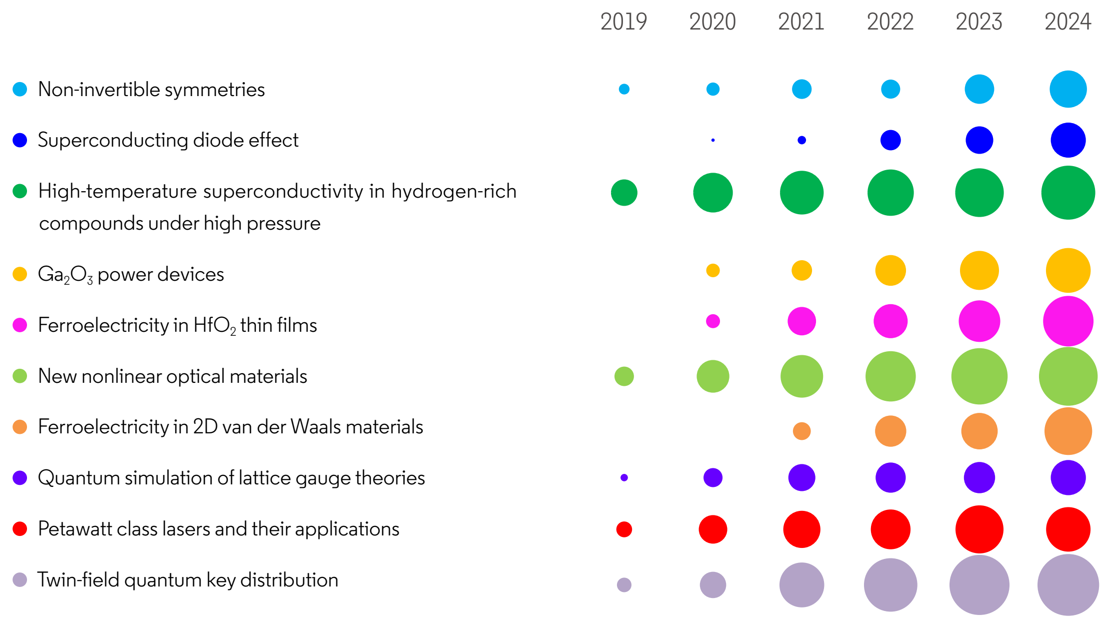


Figure 19: Citing papers for the Top 10 Research Fronts in physics

1.2 KEY HOT RESEARCH FRONT – "Superconducting diode effect"

The superconducting diode effect (SDE) is a novel transport phenomenon that allows superconducting current to flow only in one direction, but oppose in the opposite direction. The nonreciprocity endows the superconducting diodes with rectification characteristics similar to those of a semiconductor diode, allowing unidirectional non-dissipative current transmission while presenting a finite resistance in the reverse direction. Superconducting diodes will provide new device applications for superconducting electronics, superconducting spintronics, and quantum technologies.

Theoretical study of the SDE has been carried out for many years. However, experimental realization of superconducting diodes has remained a significant challenge. In 2020, researchers at Kyoto University and other institutions reported the first observation of the SDE in Nb/V/Ta superlattice superconductors with an applied magnetic field. This discovery attracted widespread attention from both theorists and experimentalists. The SDE without a magnetic field was revealed in $NbSe_2/Nb_3Br_8/NbSe_2$ Josephson junctions by researchers at Delft University of Technology and their collaborators in 2022. In recent years, the SDE has been discovered in various superconducting systems, including chiral superconductors, superconductors with strong spin-orbit coupling, Josephson junctions, and superconducting films. The progress has advanced research on the SDEs and their material systems, providing a feasible path for the development of ultra-low-power electronic devices.

As for the citation frequency of individual core papers (Figure 20), among the 22 core foundational reports, the most frequently cited is a 2020 study by researchers at Kyoto University and their collaborators. This paper reported the first observation of the SDE; this report has now been cited more than 260 times. Another report on the SDE based on Josephson junctions, published in 2022 by the University of Regensburg in Germany and its collaborators, and another 2022 report on the discovery of non-magnetic SDE by researchers at Delft University of Technology in the Netherlands and their collaborators, have respectively earned citation counts of 191 and 177 at this writing.

In addition, research findings in 2022 from institutions including MIT on the SDE of 2D superconductors with strong spin-orbit coupling, Kyoto University on the mechanism of SDE, the Max Planck Institute of Microstructure Physics in Halle, Germany on the SDE of topological semimetals, and Brown University on the SDE of twisted trilayer graphene, have been also widely cited.

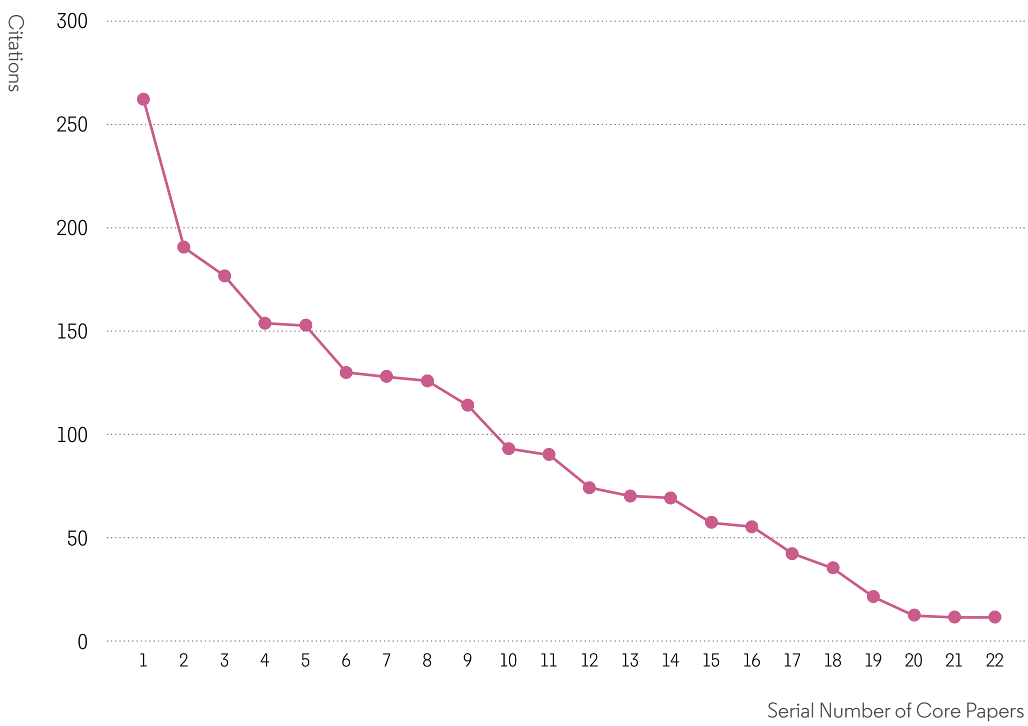


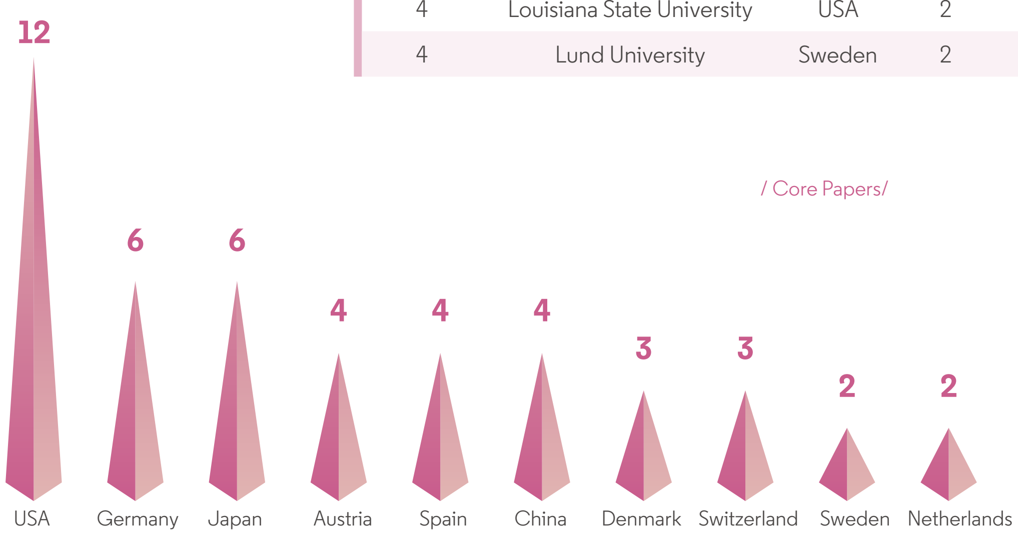
Figure 20: Citation frequency distribution curve of core papers in the Research Front "Superconducting diode effect"

In this front, the USA is the most prolific and the primary country producing the core papers, participating in 12 core reports and accounting for 54.5% of the total (Table 38). Authors based in Germany and Japan each contributed six core papers, accounting for 27.3%. Austria, China, and Denmark also performed well. Among individual organizations, MIT contributed the highest number of core papers. On the list of top institutions (14 in total, including ties), three are based in the USA and three in Spain, while Japan, Germany, and Austria are each host to two, and Denmark and Sweden each claim one.

Table 38: Top countries and institutions producing core papers in the Research Front "Superconducting diode effect"

Country Ranking	Country	Core Papers	Proportion
1	USA	12	54.5%
2	Germany	6	27.3%
2	Japan	6	27.3%
4	Austria	4	18.2%
4	Spain	4	18.2%
4	China	4	18.2%
7	Denmark	3	13.6%
7	Switzerland	3	13.6%
9	Sweden	2	9.1%
9	Netherlands	2	9.1%

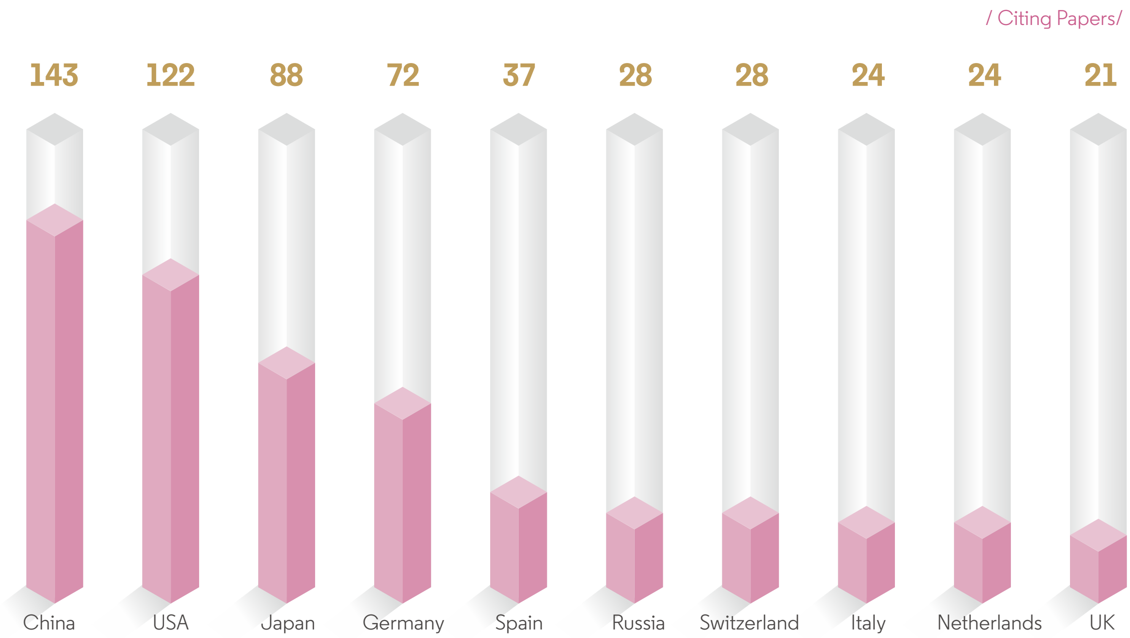
Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Massachusetts Institute of Technology (MIT)	USA	4	18.2%
2	Purdue University	USA	3	13.6%
2	University of Copenhagen	Denmark	3	13.6%
4	National Institute of Materials Science (Nims) - Japan	Japan	2	9.1%
4	Kyoto University	Japan	2	9.1%
4	Max Planck Society	Germany	2	9.1%
4	University of Regensburg	Germany	2	9.1%
4	Spanish National Research Council (CSIC)	Spain	2	9.1%
4	University of the Basque Country	Spain	2	9.1%
4	Donostia International Physics Center	Spain	2	9.1%
4	Institute of Science and Technology Austria	Austria	2	9.1%
4	University of Innsbruck	Austria	2	9.1%
4	Louisiana State University	USA	2	9.1%
4	Lund University	Sweden	2	9.1%



In terms of papers that cite the core literature (Table 39), China and the USA are the most active countries, followed by Japan and Germany. On the list of citing institutions, the Chinese Academy of Sciences published the most citing papers. RIKEN, University of Tokyo, and Kyoto University rank 2nd to 4th. Among the top citing institutions, Japan hosts three, while Spain claims two, and China, Italy, France, Russia, and Germany are each home to one.

Table 39: Top countries and institutions producing citing papers in the Research Front "Superconducting diode effect"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	143	31.2%	1	Chinese Academy of Sciences	China	49	10.7%
2	USA	122	26.6%	2	Riken	Japan	35	7.6%
3	Japan	88	19.2%	3	University of Tokyo	Japan	27	5.9%
4	Germany	72	15.7%	4	Kyoto University	Japan	25	5.4%
5	Spain	37	8.1%	5	Italian National Research Council (CNR)	Italy	19	4.1%
6	Russia	28	6.1%	6	National Center for Scientific Research of France (CNRS)	France	17	3.7%
6	Switzerland	28	6.1%	6	Russian Academy of Sciences	Russia	17	3.7%
8	Italy	24	5.2%	8	Donostia International Physics Center	Spain	16	3.5%
8	Netherlands	24	5.2%	9	Max Planck Society	Germany	15	3.3%
10	UK	21	4.6%	9	University of Science and Technology of China	China	15	3.3%
				9	University of the Basque Country	Spain	15	3.3%



1.3 KEY HOT RESARCH FRONT– “Petawatt-class lasers and their applications”

Petawatt-class lasers are high-power laser systems with an output power exceeding one quadrillion watts (10^{15} W), creating unprecedented extreme optical field conditions. Petawatt lasers are of great significance in fields such as fundamental science, energy, and healthcare. They provide extreme experimental platforms for quantum electrodynamics and dark matter detection, drive inertial confinement fusion or laser-wakefield acceleration to generate high-quality charged particle beams, and produce high-energy particles for tumor therapy and medical imaging.

The first petawattclass laser was commissioned in 1996 at the Lawrence Livermore National Laboratory in the USA. In 2004, the Vulcan laser at the Central Laser Facility (CLF) in the UK became the first petawatt laser operated as a user facility. Subsequently, major countries around the world have built and brought online their own petawatt lasers. In recent years, several nations and regions have been constructing 10 PW lasers and advancing toward 100 PW systems, such as the Extreme Light Infrastructure (ELI) in the Europe, Shanghai Superintense Ultrafast Laser Facility (SULF) in China, Optical Parametric Amplifier Line (OPAL) in the USA, and the XCELS (eXawatt Center for Extreme Light Studies) project in Russia. By leveraging the development of these higher-power laser technologies, scientists have achieved a series of important advancements, such as obtaining GeV level electron beam and producing ultra-high proton dose rates for tumor therapy. In the future, the development of more advanced petawatt lasers will provide better extreme physical conditions for leading-edge scientific research.

As for the citation impact of individual core papers (Figure 21), two papers published in 2019 have garnered the highest citation counts, including a review article on petawatt and exawatt class lasers by researchers at the UK Atomic Weapons Agency (AWE) and collaborators (cited 578 times as this writing), and a report on work that generated electron beams with energies up to 7.8 GeV in a 20-cm-long plasma by Lawrence Berkeley National Laboratory and partners (cited 537 times to date).

Also achieving distinction in citation counts: a 2021 study by the Institute for Basic Science (IBS) in South Korea, which used a petawatt-class laser at the Center for Relativistic Laser Science (CoReLS) to achieve ultrahigh-intensity laser pulses exceeding 10^{23} W/cm^2; a 2021 report by Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, which realized a 27-nm free-electron laser using a laser-wakefield electron accelerator; and a 2023 review by a team at the National Research Nuclear University MEPhI in Russia and collaborators, on strong-field quantum chromodynamics research using high-intensity laser facilities. To date, these studies have been cited 270, 159 and 153, respectively.

In addition, two other papers have also received significant attention: a 2022 study by the Helmholtz-Zentrum Dresden-Rossendorf in Germany and collaborators, which successfully tested the irradiation of mouse tumors with a laser-accelerated proton beam, along with a 2022 report by the National Institute for Physics and Nuclear Engineering in Romania and collaborators, which achieved the generation and delivery of 10.2 PW peak power laser pulses using the high-power laser system at the Extreme Laser Infrastructure – Nuclear Physics facility (ELI-NP) facility.

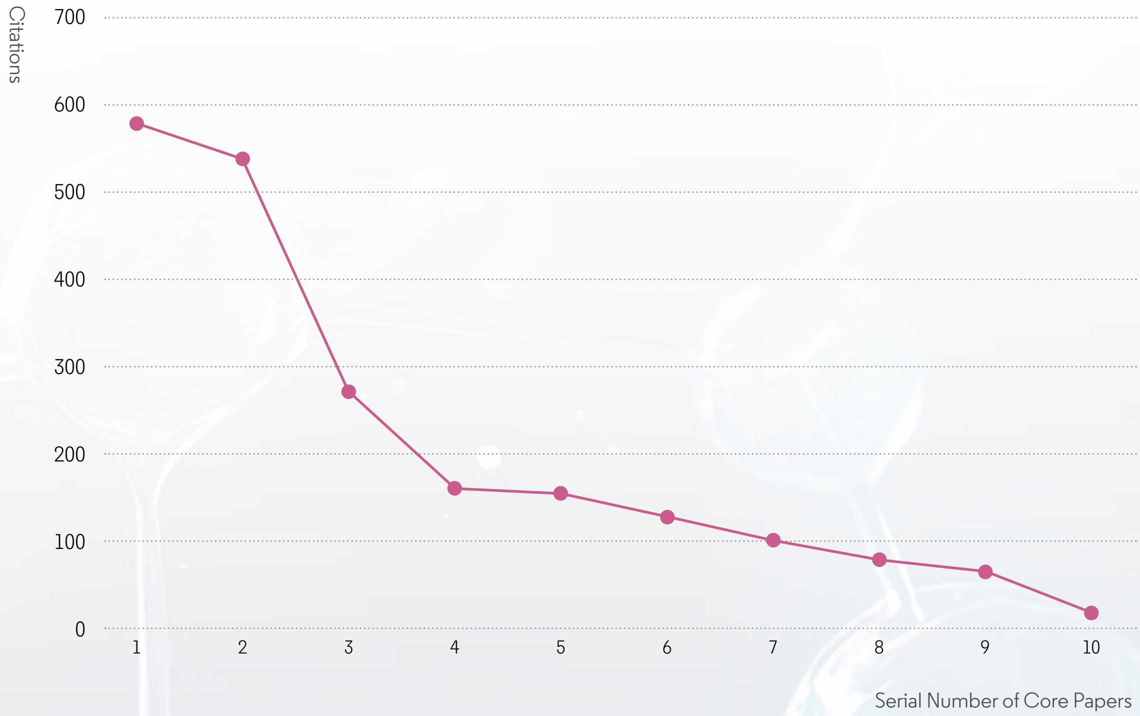


Figure 21: Citation frequency distribution curve of core papers in the Research Front "Petawatt class lasers and their applications"

The USA and Germany are the most active countries in this front. Authors based in the two nations each participated in five core papers (Table 40), accounting for 50% of the total. The UK, Japan, Russia, and France also show notable contributions. Among individual organizations, the Helmholtz Association in Germany contributed the highest numbers of core papers. The list of top institutions (including ties) features 22, with the USA and the UK both host to four, with Germany and France each containing three, South Korea and Russia each claiming two, and China, the Czech Republic, Italy and Japan each home to one.

Table 40: Top countries and institutions producing core papers in the Research Front "Petawatt class lasers and their applications"

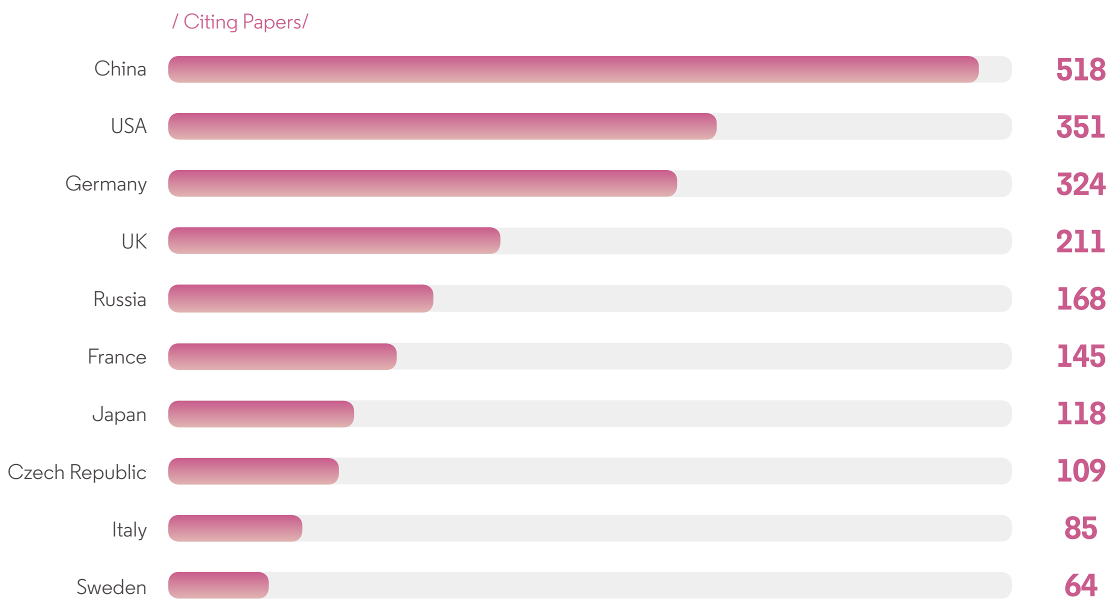
Country Ranking	Country	Core Papers	Proportion
1	USA	5	50.0%
1	Germany	5	50.0%
3	UK	4	40.0%
3	Japan	4	40.0%
5	Russia	3	30.0%
5	France	3	30.0%
7	China	2	20.0%
7	Sweden	2	20.0%
7	Italy	2	20.0%
7	South Korea	2	20.0%
7	Czech Republic	2	20.0%

Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	Helmholtz Association	Germany	4	40.0%
2	Lawrence Berkeley National Laboratory	USA	3	30.0%
2	Lawrence Livermore National Laboratory	USA	3	30.0%
4	Chinese Academy of Sciences	China	2	20.0%
4	University of Texas Austin	USA	2	20.0%
4	University of Michigan	USA	2	20.0%
4	STFC Rutherford Appleton Laboratory	UK	2	20.0%
4	UK Research and Innovation	UK	2	20.0%
4	Imperial College London	UK	2	20.0%
4	University of Strathclyde	UK	2	20.0%
4	National Center for Scientific Research of France (CNRS)	France	2	20.0%
4	French Alternative Energies and Atomic Energy Commission (CEA)	France	2	20.0%
4	Sorbonne University	France	2	20.0%
4	Friedrich Schiller University Jena	Germany	2	20.0%
4	University of Munich	Germany	2	20.0%
4	Institute for Basic Science	South Korea	2	20.0%
4	Gwangju Institute of Science & Technology	South Korea	2	20.0%
4	Russian Academy of Sciences	Russia	2	20.0%
4	National Research Nuclear University MEPhI	Russia	2	20.0%
4	Czech Academy of Sciences	Czech Republic	2	20.0%
4	Italian National Research Council (CNR)	Italy	2	20.0%
4	Osaka University	Japan	2	20.0%

Analysis of the citing papers (Table 41) indicates that China is the most active country, showing great interest to this research direction. The USA, Germany, and the UK follow closely behind. Among the Top 10 institutions ranked by total citations, the Chinese Academy of Sciences contributed the highest numbers of citing papers, followed by the Helmholtz Association, the Russian Academy of Sciences, and the National Center for Scientific Research of France (CNRS). On the list of citing institutions, three of the top entities are based in China, while France is host to two, and Germany, Russia, the USA, the Czech Republic, and Japan each have one.

Table 41: Top countries and institutions producing citing papers in the Research Front "Petawatt class lasers and their applications"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	518	33.8%	1	Chinese Academy of Sciences	China	252	16.4%
2	USA	351	22.9%	2	Helmholtz Association	Germany	190	12.4%
3	Germany	324	21.1%	3	Russian Academy of Sciences	Russia	134	8.7%
4	UK	211	13.8%	4	National Center for Scientific Research of France (CNRS)	France	119	7.8%
5	Russia	168	11.0%	5	Shanghai Jiao Tong University	China	85	5.5%
6	France	145	9.5%	6	French Alternative Energies and Atomic Energy Commission (CEA)	France	83	5.4%
7	Japan	118	7.7%	7	Lawrence Berkeley National Laboratory	USA	80	5.2%
8	Czech Republic	109	7.1%	8	Czech Academy of Sciences	Czech Republic	74	4.8%
9	Italy	85	5.5%	9	Peking University	China	65	4.2%
10	Sweden	64	4.2%	10	National Institutes for Quantum Science and Technology, QST	Japan	61	4.0%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN PHYSICS

One topic in physics is highlighted as an emerging Research Front: "High-temperature superconductivity in Bilayer Nickelate Superconductor $La_3Ni_2O_7$ ".

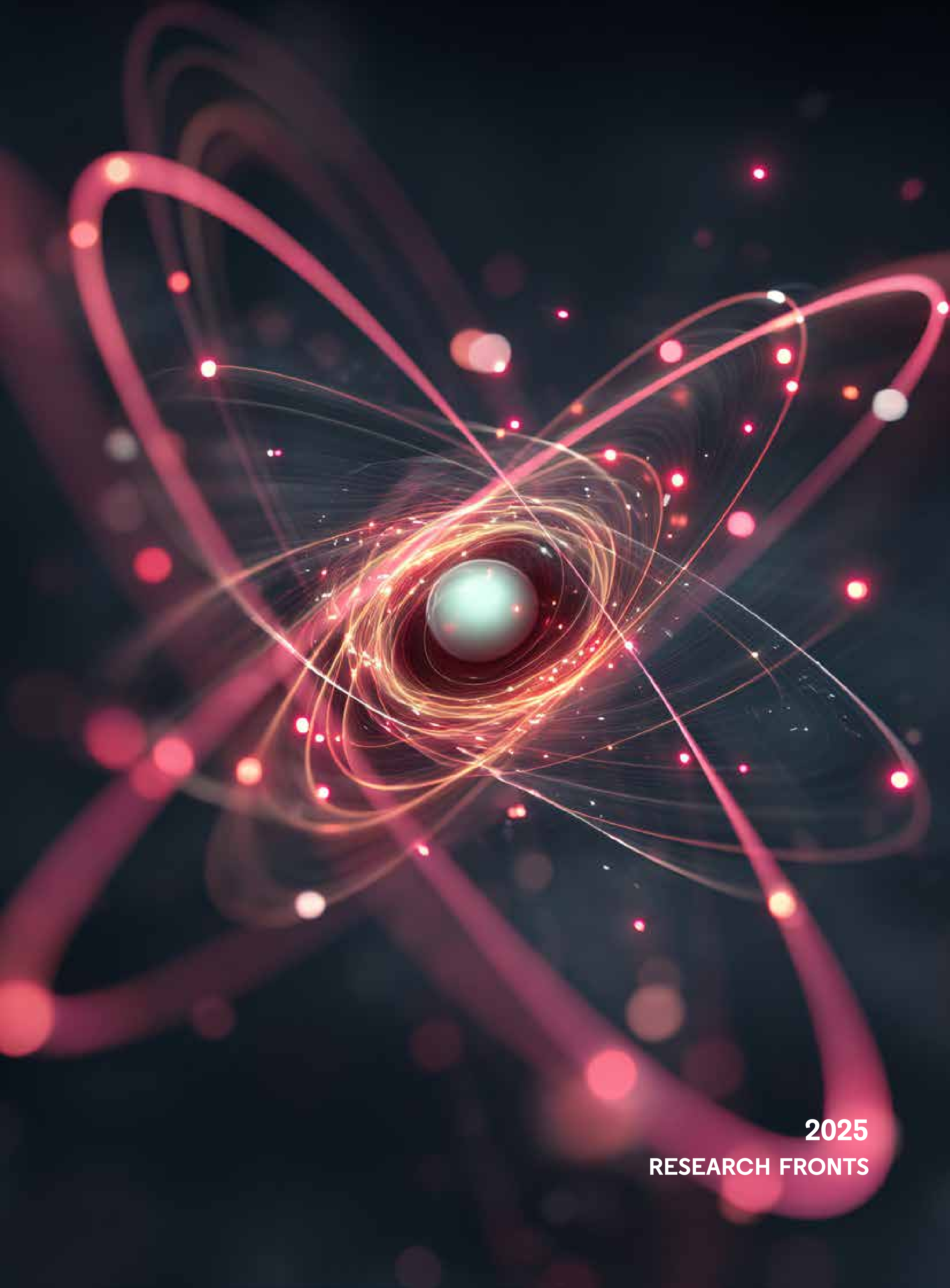
Table 41: Emerging Research Front in physics

Rank	Emerging Research Front	Core papers	Citation	Mean Year of Core Papers
1	High-temperature superconductivity in Bilayer Nickelate Superconductor $La_3Ni_2O_7$	43	1757	2023.6

2.2 KEY EMERGING RESEARCH FRONT – "High-temperature superconductivity in Bilayer Nickelate Superconductor $La_3Ni_2O_7$"

Superconductivity research has long been a significant and cutting-edge topic in condensed matter physics, with scientists continuously striving to discover superconductors with higher superconducting critical temperatures (Tc) and to reveal the specific mechanism of superconductivity. Currently, the highest Tc for a conventional superconductor at ambient pressure is 39 K, while that of unconventional superconductors is 133K at ambient pressure and belongs to the cuprates. Among unconventional superconductors, such as cuprates, iron-based superconductors and heavy-fermion superconductors, cuprates are the only ones that host high Tc above the boiling point of liquid nitrogen (77 K) at ambient pressure.

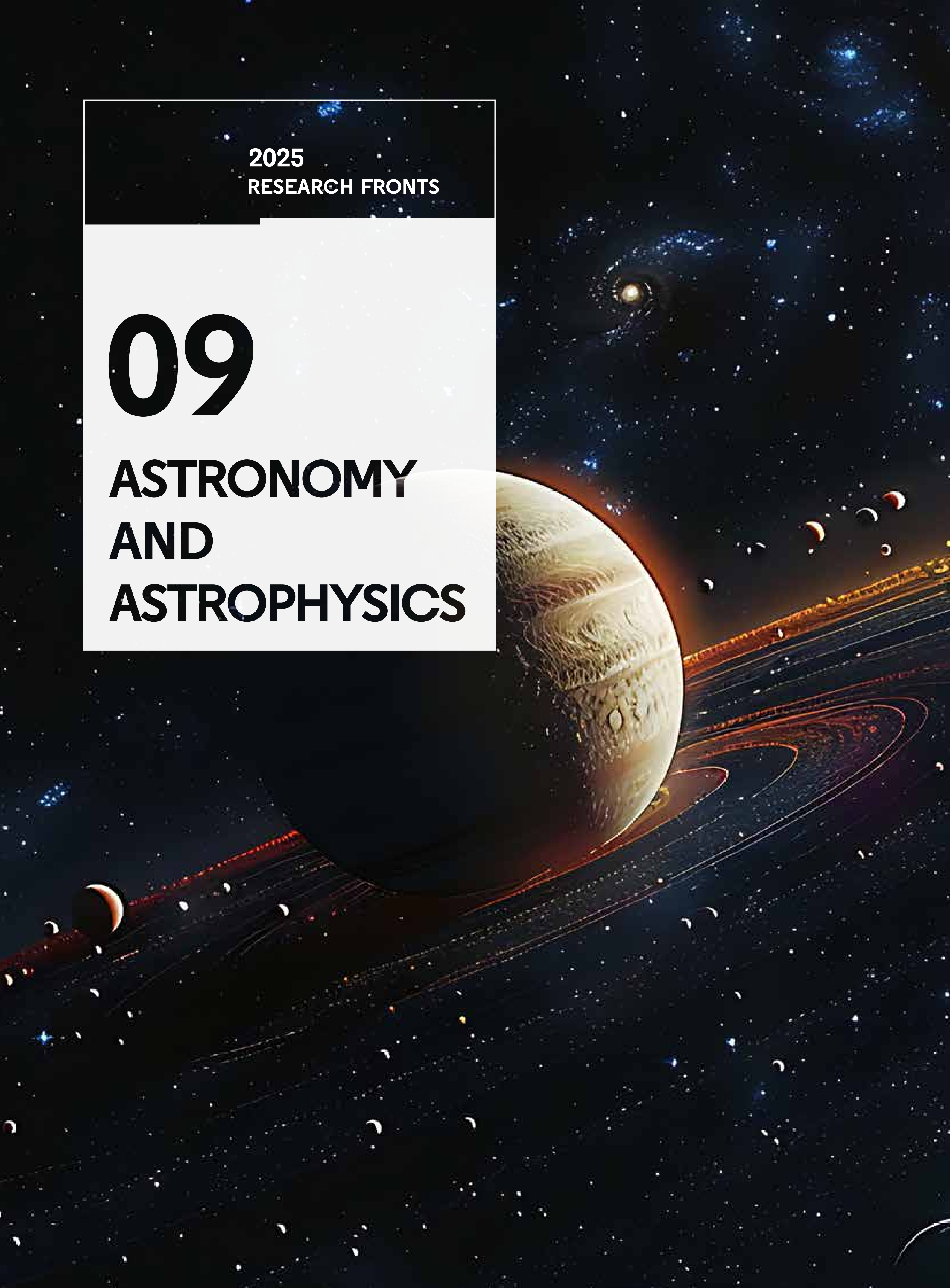
In 2019, researchers at Stanford University and their collaborators reported the observation of superconductivity in the $Nd_{0.8}Sr_{0.2}NiO_2$ system with a maximal Tc of 15K. This achievement has stimulated wider interest in nickel oxide superconductors. In 2023 and 2024, the specialty of superconductivity of infinite layer nickelates was continuously selected as a hot Research Front. In 2023, researchers at Sun Yat-sen University, China, and their collaborators discovered superconductivity with Tc near 80K under a high pressure of above 14 GPa in a bilayer nickelate $La_3Ni_2O_7$, which is the second type of unconventional superconductor with Tc above liquid nitrogen temperature. This advance has triggered an upsurge in the study of nickel-based superconductors. In this emerging front, a paper published by a team at Sun Yat-sen University and their colleagues, on the discovery of superconductivity in bilayer nickelates, has achieved the highest citation, currently at 197. Other papers focus on the physical properties and superconducting mechanism of $La_3Ni_2O_7$ system through theoretical and computational studies.


2025
RESEARCH FRONTS

2025
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 detection and gravity theories; neutron star properties; various cosmological probes; Gaia and Fermi surveys; fast radio bursts; and direct detection of dark matter. Research on gravitational waves detection and gravity theories, as well as related extended studies on the properties of dense celestial bodies, have attracted widespread attention. Related Research Fronts include nanohertz gravitational waves detected by pulsar timing arrays; gravity theories and cosmology; and multi-messenger constraints on neutron star properties.

Research topics in cosmology remain prominent, including cosmological constraints based on light curves of supernovae; cosmic shear surveys; and cosmological parameter measurements from Baryon Oscillation Spectroscopic Survey (BOSS) data. The major space-based observatories continue to produce high-quality outputs, including Gaia Data Release 3 and observation of the Milky Way and the gamma-ray sources and AGNs catalogs of the Fermi LAT. The observations and properties of fast radio bursts have once again made the list. Dark matter detection focuses on direct detection of low-mass dark matter candidates.

Table 43: Top 10 Research Fronts in astronomy and astrophysics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Nanohertz gravitational waves detected by pulsar timing arrays	37	3927	2023.3
2	**Cosmological constraints based on light curves of supernovae**	**2**	**640**	**2022.0**
3	Gravity theories and cosmology	33	4383	2021.5
4	Gaia Data Release 3 and observation of the Milky Way	42	7158	2021.2
5	Cosmic shear surveys and cosmology	9	2653	2020.9
6	Multi-messenger constraints on neutron star properties	25	8048	2020.8
7	Cosmological parameter measurements from BOSS data	5	984	2020.8
8	Observations and properties of fast radio bursts	41	8238	2020.7
9	The gamma-ray sources and AGNs catalogs of the Fermi LAT	3	1217	2020.7
10	**Searching for low-mass dark matter candidates via direct detection experiment**	**19**	**3632**	**2020.6**

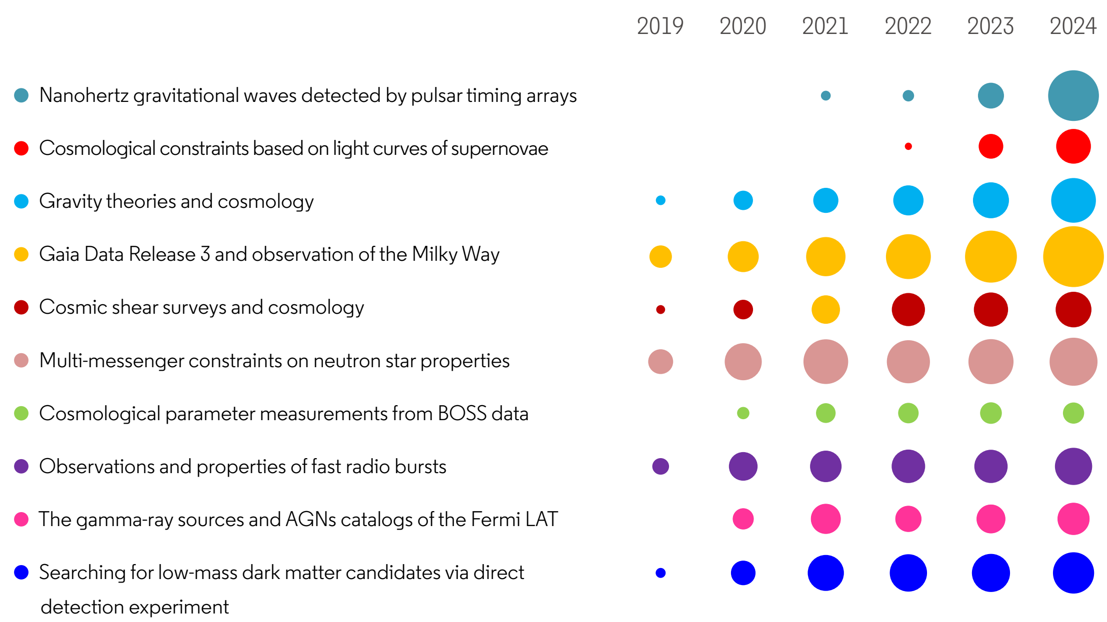


Figure 22: Citing papers for the Top 10 Research Fronts in astronomy and astrophysics

1.2 KEY HOT RESEARCH FRONT – "Cosmological constraints based on light curves of supernovae"

A supernova is a powerful and luminous stellar explosion. This transient astronomical event occurs during the last evolutionary stages of a massive star or when a white dwarf is triggered into runaway nuclear fusion. The resulting explosion causes the star to shine brightly for some time before fading.

Among the different types of supernovae, Type Ia supernovae have a special place in the field of astronomy. They are known as "standardizable candles" to measure cosmological distances. By observing the light curve of a Type Ia supernova, astronomers can determine its peak luminosity, correct for any variations using the Phillips relation, and then calculate its distance from Earth. Research has confirmed the advantages of this method in measuring galaxy distances. Type Ia supernovae anchor the standard model of cosmology with their unmatched ability to map the past 10 billion years of expansion history.

Type Ia supernovae provided the first evidence of the accelerating expansion of the universe. The 2011 Nobel Prize in Physics was awarded to Saul Perlmutter, Brian P. Schmidt and Adam G. Riess for the discovery of the accelerating expansion of the universe through observations of distant supernovae. Type Ia supernovae remain invaluable because they are bright enough to be seen at large cosmic distances, common enough to be found in large numbers, and able to be standardized to ~0.1 mag precision in brightness or ~5% in distance per object. In recent years, the sample size of Type Ia supernova has continuously increased, becoming a key pillar for gaining deeper insights into the standard model of cosmology.

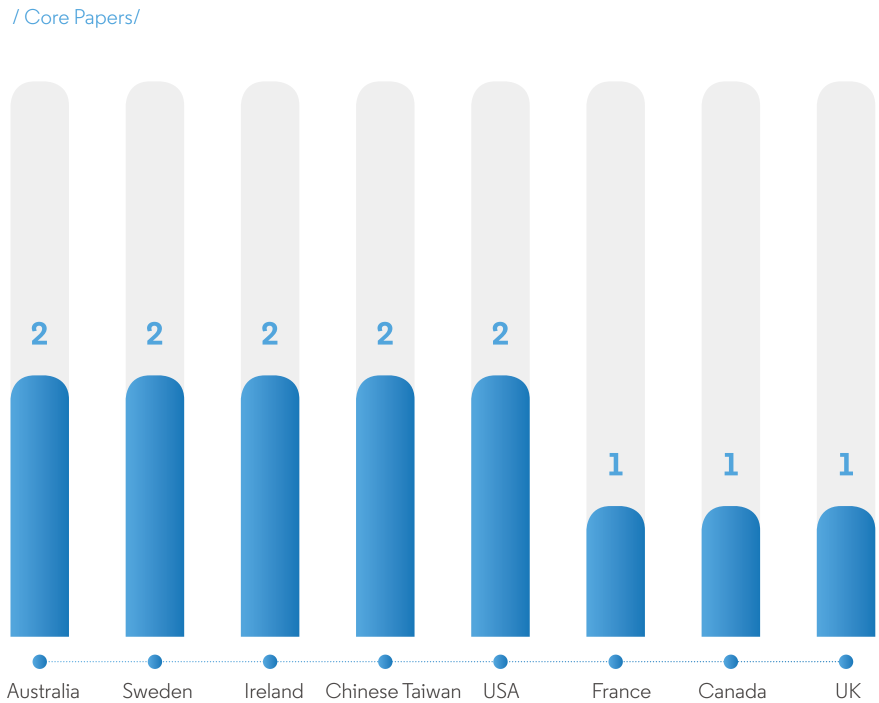
The hot Research Front "Cosmological constraints based on light curves of supernovae" includes two core papers, which are also two of the four series papers published in 2022 in *The Astrophysical Journal*. This work presented 1,701 light curves of 1,550 unique, spectroscopically confirmed Type Ia supernovae that would be used to infer cosmological parameters.

One core paper released the full data set and light curves which were compiled across 18 different surveys, including Type Ia supernovae measured over the entire redshift range, from z = 0 to z = 2.3, aiming to perform an extensive review of redshifts, peculiar velocities, photometric calibration, and intrinsic-scatter models of Type Ia supernovae. The other core paper described the methodology, from fitting supernovae light curves to constraining cosmological parameters, also summarizing all the inputs to the analysis including the data sample, calibration, and redshifts, and presenting the cosmological results. This work featured an increased sample size from the addition of multiple cross-calibrated photometric systems of supernovae covering an increased redshift span, and improved treatments of systematic uncertainties, which together enabled more precise constraints on cosmological parameters.

Both core papers were co-authored by dozens of authors from multiple institutions worldwide. Regarding the core papers contributions by country/region, Australia, Sweden, Ireland, the USA, and Chinese Taiwan each contributed two papers, while France, Canada, and the UK each contributed one. As for contributions by institutions, 10 American institutions, including the University of California Santa Cruz, Johns Hopkins University, the Smithsonian Institution, Duke University, the University of California Berkeley, Texas A&M University, Rutgers University, the University of Notre Dame, the Association of Universities for Research in Astronomy, and the Space Telescope Science Institute, as well as the University of Queensland in Australia, Trinity College Dublin in Ireland, and the National Central University in Chinese Taiwan each contributed two core papers.

Table 44: Top countries/region and institutions producing core papers in the Research Front "Cosmological constraints based on light curves of supernovae"

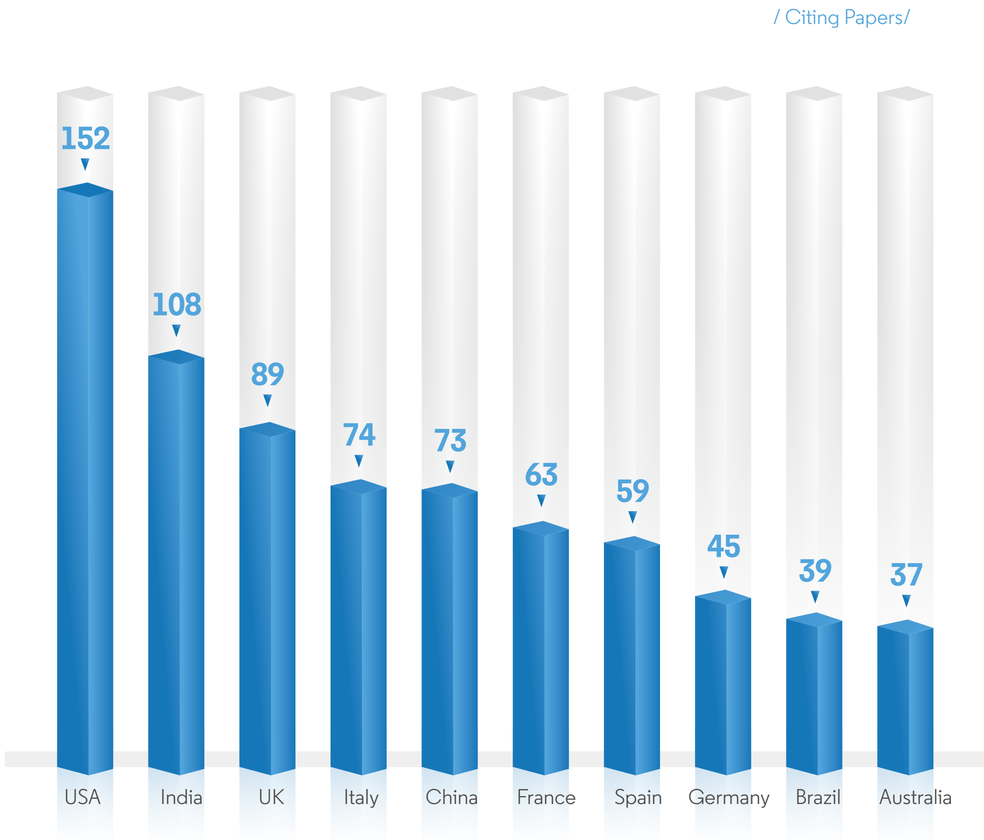
Country Ranking	Country/ Region	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country/Region	Core Papers	Proportion
1	Australia	2	100.0%	1	University of California Santa Cruz	USA	2	100.0%
1	Sweden	2	100.0%	1	Johns Hopkins University	USA	2	100.0%
1	Ireland	2	100.0%	1	Smithsonian Institution	USA	2	100.0%
1	Chinese Taiwan	2	100.0%	1	Duke University	USA	2	100.0%
1	USA	2	100.0%	1	University of California Berkeley	USA	2	100.0%
6	France	1	50.0%	1	Texas A&M University	USA	2	100.0%
6	Canada	1	50.0%	1	Rutgers University	USA	2	100.0%
6	UK	1	50.0%	1	University of Notre Dame	USA	2	100.0%
				1	Association of Universities for Research in Astronomy	USA	2	100.0%
				1	Space Telescope Science Institute	USA	2	100.0%
				1	University of Queensland	Australia	2	100.0%
				1	Trinity College Dublin	Ireland	2	100.0%
				1	National Central University	Chinese Taiwan	2	100.0%



As for citing papers, the USA ranks 1st, followed by India, the UK, Italy, and China. In terms of the citing institutions, the National Center for Scientific Research in France ranks 1st, followed by the National Institute of Nuclear Physics in Italy and Duke University in the USA. It is worth noting that the Chinese Academy of Sciences also performs strongly in terms of citing papers, ranking 8th.

Table 45: Top countries and institutions producing citing papers in the Research Front "Cosmological constraints based on light curves of supernovae"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	152	30.5%	1	National Center for Scientific Research of France (CNRS)	France	57	11.4%
2	India	108	21.6%	2	National Institute of Nuclear Physics (INFN)	Italy	40	8.0%
3	UK	89	17.8%	3	Duke University	USA	39	7.8%
4	Italy	74	14.8%	4	University of Chicago	USA	35	7.0%
5	China	73	14.6%	5	Johns Hopkins University	USA	32	6.4%
6	France	63	12.6%	6	Smithsonian Institution	USA	31	6.2%
7	Spain	59	11.8%	6	Space Telescope Science Institute	USA	31	6.2%
8	Germany	45	9.0%	8	Chinese Academy of Sciences	China	30	6.0%
9	Brazil	39	7.8%	9	University of Cambridge	UK	28	5.6%
10	Australia	37	7.4%	10	Spanish National Research Council (CSIC)	Spain	27	5.4%



1.3 KEY HOT RESEARCH FRONT – "Searching for low-mass dark matter candidates via direct detection experiment"

According to the prevailing cosmological model, dark matter constitutes about 27% of the matter in the universe, yet its fundamental nature remains a mystery. Currently, the experimental methodologies for searching for dark matter particles are mainly divided into three categories: indirect detection, collider searches, and direct detection.

Among these methods, direct detection is the most straightforward for confirming the particulate nature of dark matter. It involves using detectors deployed deep underground with extremely low background noise to directly capture the faint signals produced when dark matter particles collide with the nuclei or electrons of ordinary matter. Over the past few decades, direct detection experiments have primarily focused on searching for the theoretically favored weakly interacting massive particles (WIMPs), whose masses were generally considered to be above GeV/c^2.

However, despite continuous improvements in experimental sensitivity, no conclusive discovery has been made to date. Consequently, the research focus has expanded to include a broader range of theoretical candidates, particularly low-mass dark matter in the sub-GeV/c^2 range. These low-mass particles produce even fainter interaction signals, pushing the requirements for detector energy thresholds and background rejection capabilities to unprecedented levels.

The key Hot Research Front "Searching for low-mass dark matter candidates via direct detection experiment" includes 19 core papers, which mainly focus on four core research themes.

In terms of advancing the sensitivity of traditional WIMP detection using ton-scale liquid xenon/liquid argon detectors, major international collaborations using liquid xenon or argon detectors are in a highly competitive race to continuously lower the exclusion limits for WIMPs. The LUX-ZEPLIN (LZ) collaboration, led by the USA, utilized a 5.5-ton liquid xenon detector to set an upper limit of 9.2×10^{-48} cm^2 for the spin-independent interaction cross-section between a 36 GeV/c^2 WIMP and a nucleon, with the results published in 2023. The XENON collaboration, led by European institutions, also achieved top-tier sensitivity on the order of 10^{-48} cm^2 using the XENONnT (5.9-ton) detector. The China PandaX collaboration, led by Shanghai Jiao Tong University, benefiting from the deep-shielded environment of the China JinPing Underground Laboratory, reported a detection result of 3.8×10^{-47} cm^2 in 2021 with the PandaX-4T (3.7-ton) detector, marking China's advancement into the top tier in this field.

Regarding the development and application of novel solid-state detectors for sub-GeV dark matter, collaborations such as SENSEI and DAMIC-M have employed skipper Charge-Coupled Devices (Skipper-CCDs) technology to successively publish, in 2020 and 2023, constraint results on the interaction between sub-GeV/c^2 dark matter and electrons, opening a new window for dark matter detection in the MeV/c^2 mass range.

In enhancing detection capabilities through new physical effects, researchers have begun to utilize secondary processes such as the Migdal effect or bremsstrahlung to probe lower-mass dark matter that is unreachable by traditional methods. The XENON1T collaboration successfully used this approach in 2019 to extend the sensitivity of dark matter detection down to the mass range of approximately 85 MeV/c^2.

In the exploration of new physical processes and the expansion of detection targets, although the low-energy electron recoil excess reported by the XENON1T experiment in 2020 was not confirmed by subsequent experiments, its initial significance of up to 3.4σ for the solar axion model has greatly boosted research enthusiasm for using such detectors to discover new physics.

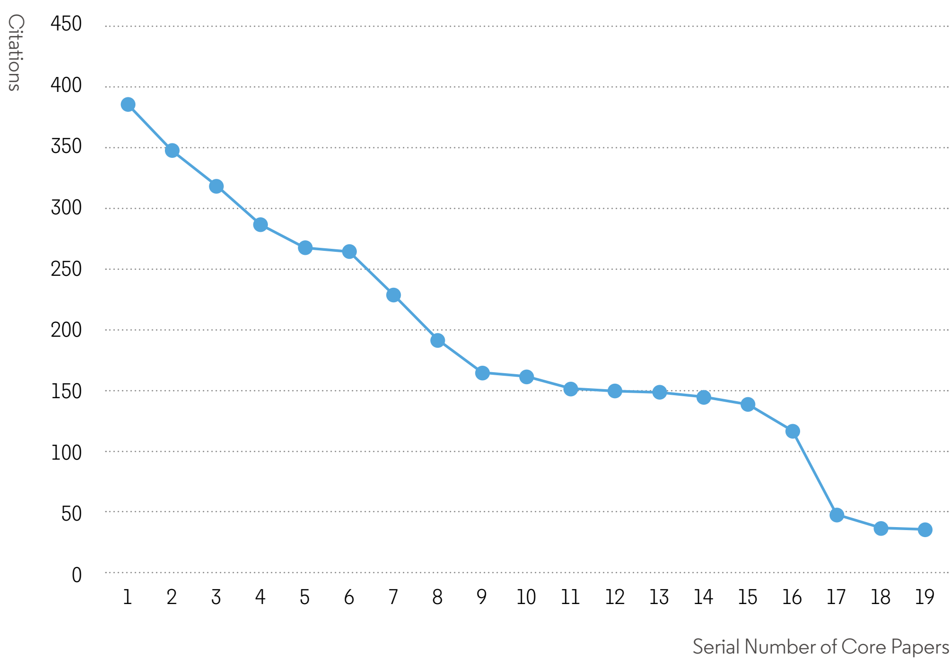


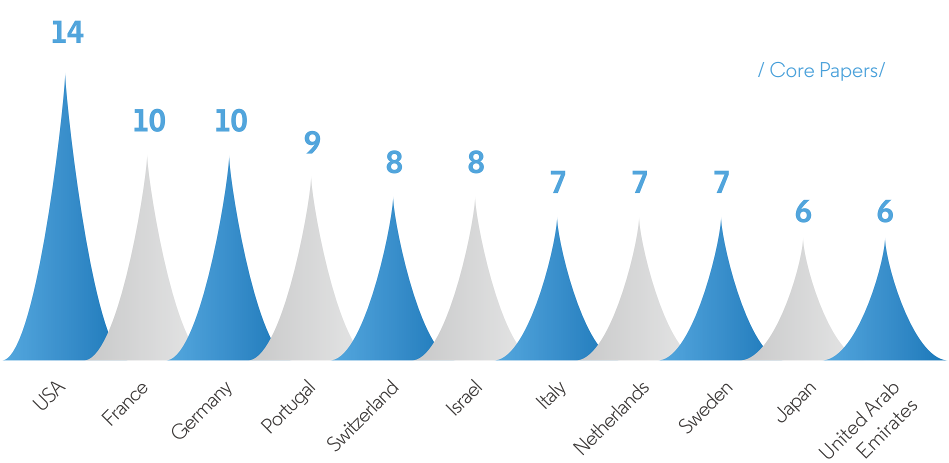
Figure 23: Citation frequency distribution curve of core papers in the Research Front "Searching for low-mass dark matter candidates via direct detection experiment"

According to the analysis of core papers by country and institution, the global research efforts are characterized by a pattern dominated by the USA and European countries, with active participation from multiple nations. The USA leads in core paper contributions, followed by France and Germany. These three countries are also the core powers behind top experiments like LZ and XENON. Active contributions also come from Portugal, Switzerland, Israel, and Italy, underscoring the highly international and collaborative nature of research in this area.

China ranks 12th in the number of core papers, and although it has not entered the top 10, the related research and contributions from the PandaX collaboration have been widely recognized. At the institutional level, the University of Chicago in the USA leads, having contributed to 11 core papers (57.9%), highlighting its leading position in this front. France-based institutions also performed well due to their deep involvement in European-led collaborations such as XENON. The National Center for Scientific Research of France (CNRS) ranked 2nd with 10 core papers, while the University of Paris Cite and the Universidade De Coimbra tied for 3rd with nine papers each.

Table 46: Top countries and institutions producing core papers in the Research Front "Searching for low-mass dark matter candidates via direct detection experiment"

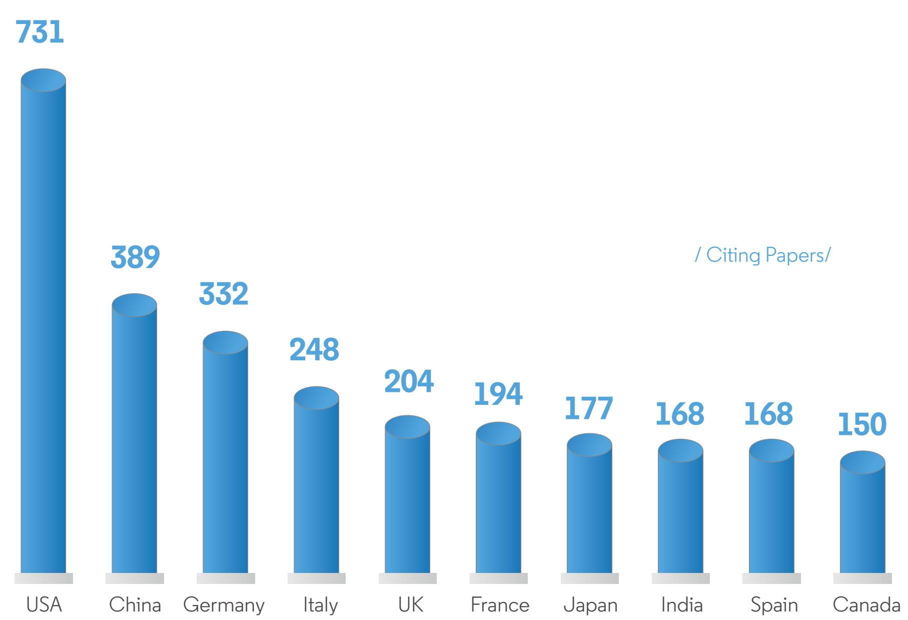
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	14	73.7%	1	University of Chicago	USA	11	57.9%
2	France	10	52.6%	2	National Center for Scientific Research of France (CNRS)	France	10	52.6%
2	Germany	10	52.6%	3	University of Paris Cite	France	9	47.4%
4	Portugal	9	47.4%	3	Universidade De Coimbra	Portugal	9	47.4%
5	Switzerland	8	42.1%	5	University Nantes Angers Le Mans	France	8	42.1%
5	Israel	8	42.1%	5	University of Nantes	France	8	42.1%
7	Italy	7	36.8%	5	IMT Inst Mines Telecommunication	France	8	42.1%
7	Netherlands	7	36.8%	5	University of Bretagne Loire	France	8	42.1%
7	Sweden	7	36.8%	5	IMT Atlantique	France	8	42.1%
10	Japan	6	31.6%	5	Sorbonne University	France	8	42.1%
10	United Arab Emirates	6	31.6%	5	University of Zurich	Switzerland	8	42.1%

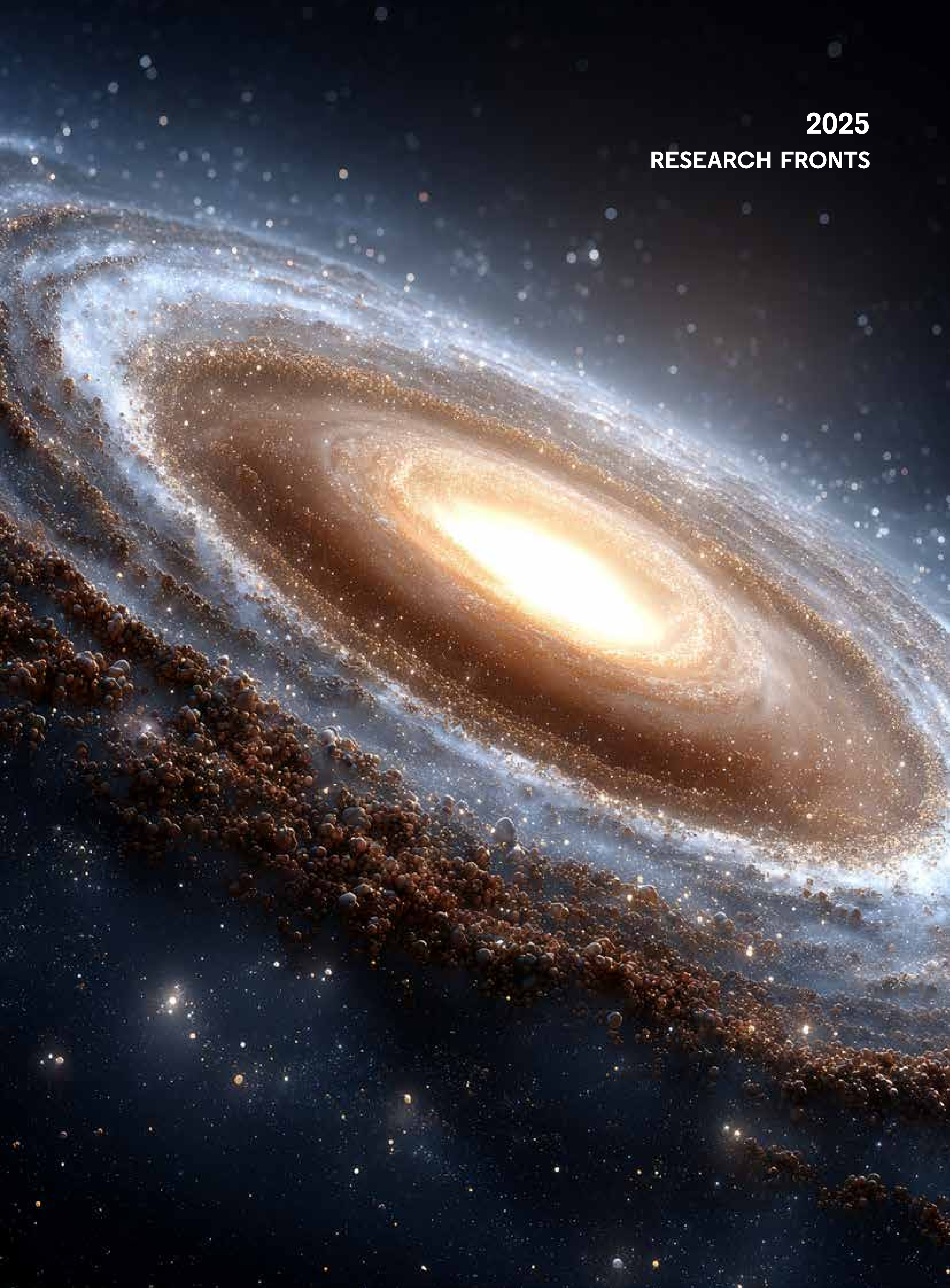


As for citing papers, the leading role of the USA is even more prominent, with a tally of 731 papers, accounting for 41.7%. China ranks 2nd with 389 papers (22.2%), demonstrating its rapidly growing influence in this research area. Germany and Italy rank 3rd and 4th, respectively. At the institutional level, the National Institute of Nuclear Physics (INFN) in Italy leads with 206 citing papers, benefiting from its operation of the Gran Sasso National Laboratory, the site of several major experiments, including XENON. The University of Chicago and the CNRS rank 2nd and 3rd, respectively, while the Chinese Academy of Sciences holds 4th place with 168 citing papers. US-based institutions occupy multiple positions, including the University of Chicago, Fermi National Accelerator Laboratory, Stanford University, and Lawrence Berkeley National Laboratory, highlights the nation's strong research capability in this field.

Table 47: Top countries and institutions producing citing papers in the Research Front "Searching for low-mass dark matter candidates via direct detection experiment"

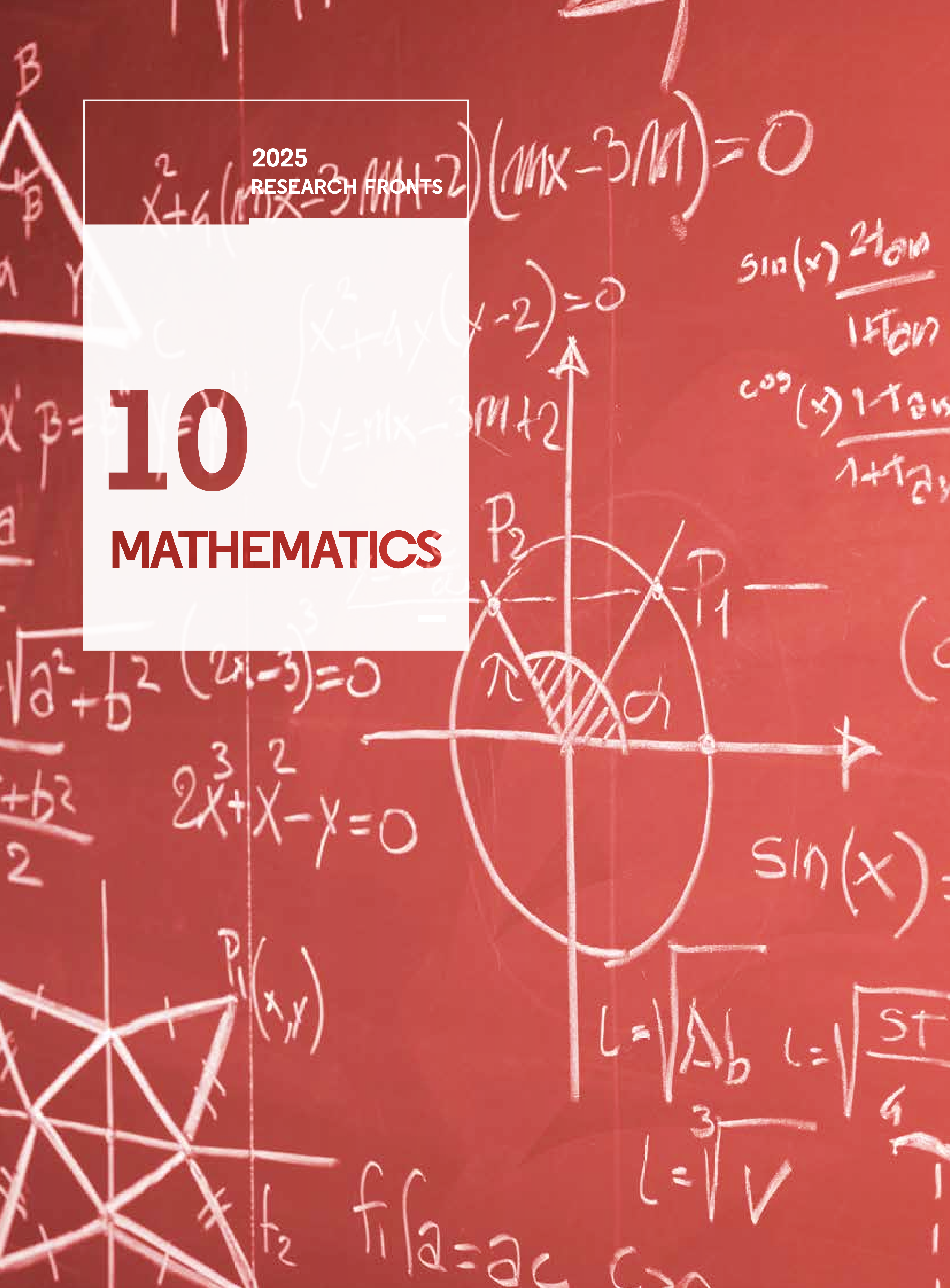
Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	731	41.7%	1	National Institute of Nuclear Physics (INFN)	Italy	206	11.8%
2	China	389	22.2%	2	University of Chicago	USA	201	11.5%
3	Germany	332	18.9%	3	National Center for Scientific Research of France (CNRS)	France	170	9.7%
4	Italy	248	14.2%	4	Chinese Academy of Sciences	China	168	9.6%
5	UK	204	11.6%	5	Fermi National Accelerator Laboratory in Illinois	USA	146	8.3%
6	France	194	11.1%	6	Max Planck Society	Germany	134	7.6%
7	Japan	177	10.1%	6	Stanford University	USA	134	7.6%
8	India	168	9.6%	8	Lawrence Berkeley National Laboratory	USA	118	6.7%
8	Spain	168	9.6%	9	Helmholtz Association	Germany	114	6.5%
10	Canada	150	8.6%	9	University of California Berkeley	USA	114	6.5%




2025
RESEARCH FRONTS

10

MATHEMATICS



1. HOT RESEARCH FRONT

1.1 TREND OF THE TOP 10 RESEARCH FRONTS IN MATHEMATICS

The Top 10 Research Fronts in mathematics mainly focus on the deep integration of machine learning and scientific computing, the profound exploration of the theoretical foundations of artificial intelligence, and optimization theory and high-dimensional statistics.

Several Hot Research Fronts have emerged from the cross-disciplinary fusion of machine learning and scientific computing. "Methods and applications of physics-informed neural networks in solving partial differential equations" and "Physics-constrained deep learning for scientific computing" are both dedicated to integrating prior physical knowledge into deep learning models. These fronts, along with "Neural operator theory, methods, and applications in scientific computing" and "Iterative optimization for computational imaging based on deep denoising priors", signify that differential equations, a long-standing hotspot in the field of mathematics, are undergoing a transformative integration with data science, giving rise to an entirely new paradigm of scientific computing.

In fundamental research on artificial intelligence (AI), "Double descent curve and generalization phenomena in modern machine learning" aims to explain why large-parameter models can possess excellent generalization capabilities, while "Optimal approximation theory for deep ReLU neural networks and applications to nonparametric regression" provides a thorough mathematical characterization of the expressive power and limits of neural networks. These Research Fronts highlight the key role that mathematics plays in the development of emerging interdisciplinary fields by providing a rigorous theoretical foundation for other domains.

Additionally, optimization theory and statistical methods have also received significant attention. Research Fronts such as "Derivative-free and zeroth-order optimization", "Scalable and exact algorithms for high-dimensional sparse regression and best subset selection", "Robust statistical inference in high-dimensional statistics", and "Theory and computation of nonlocal models and fractional differential equations" have all been selected as Top 10 Hot Research Fronts in this area.

Table 48: Top10 Research Fronts in mathematics

Rank	Hot Research Fronts	Core Papers	Citations	Mean Year of Core Papers
1	Neural operator theory, methods, and applications in scientific computing	4	1309	2021.5
2	Iterative optimization for computational imaging based on deep denoising priors	4	686	2021.3
3	Physics-constrained deep learning for scientific computing	12	3159	2020.9
4	**Double descent curve and generalization phenomena in modern machine learning**	**8**	**1084**	**2020.5**
5	Robust statistical inference in high-dimensional statistics	2	166	2020.5
6	**Methods and applications of physics-informed neural networks in solving partial differential equations**	**4**	**9263**	**2020.3**
7	Optimal approximation theory for deep ReLU neural networks and applications to nonparametric regression	15	1346	2020.3
8	Theory and computation of nonlocal models and fractional differential equations	2	368	2020.0
9	Derivative-free and zeroth-order optimization	2	224	2020.0
10	Scalable and exact algorithms for high-dimensional sparse regression and best subset selection	2	196	2020.0

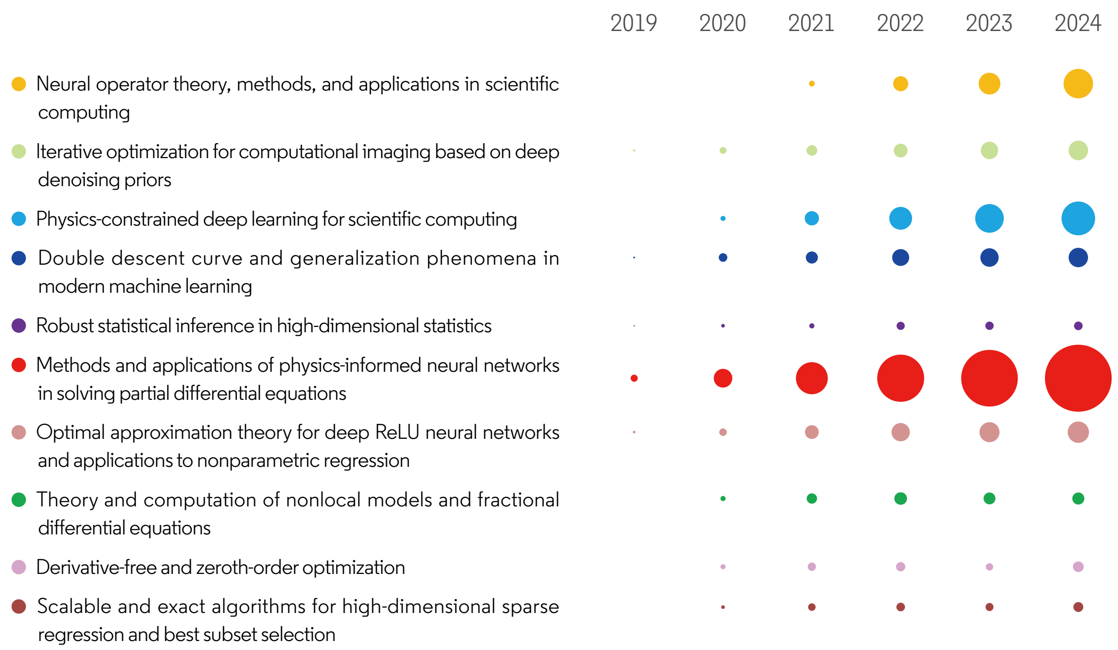


Figure 24: Citing papers for the top 10 Research Fronts in mathematics

1.2 KEY HOT RESEARCH FRONT — "Double descent curve and generalization phenomena in modern machine learning"

Modern machine learning models, represented by deep neural networks, are often highly over-parameterized with significantly more parameters than the number of training samples. This characteristic allows them to perfectly interpolate noisy training data, yet still demonstrate exceptional generalization and predictive performance on new data. This observation appears to contradict the classical bias-variance trade-off theory in statistical learning, which suggests that overly complex models should lose their ability to generalize due to overfitting, resulting in a characteristic U-shaped test error curve.

Although early research in the late 1990s noted harmless overfitting in simple models like linear classifiers, the phenomenon's broader significance was widely recognized only with the success of deep learning in the 2010s. Between 2018 and 2019, a series of pioneering works by Mikhail Belkin and colleagues at the University of California, San Diego, systematically introduced and experimentally verified the double descent risk curve.

This curve demonstrates that as model complexity increases, the test error, after reaching the peak of the traditional U-shaped curve, enters a second phase of decline, creating a "double U" shape. The finding offers a unified framework for reconciling classical theory with modern empirical observations. Once the mathematical principles underlying this phenomenon are fully revealed, they will guide the design and training of next-generation AI models and greatly enhance the interpretability and reliability of AI systems.

The key hot Research Front "Double descent curve and generalization phenomena in modern machine learning" consists of eight core papers, primarily focusing on the following three closely related topics. In the identification and unification of the double descent phenomenon, as well as the proposal of the concept of "benign overfitting", a landmark paper in the *Proceedings of the National Academy of Sciences* in 2019 first clearly depicted the double descent risk curve and pointed out that the traditional U-shaped curve is merely the first part of the double descent curve in the under-parameterized region.

Another paper published in the same journal in 2020 introduced the concept of benign overfitting and, for the first time, provided a rigorous mathematical characterization of the conditions for this phenomenon in the classic linear regression model, revealing that over-parameterization is a necessary condition for achieving benign overfitting. In terms of precise mathematical derivation and quantitative characterization of the double descent phenomenon in controllable models, research from Stanford University in 2022 successfully extended the analysis from simple linear models to more complex feature models, including single-layer random neural networks, using tools such as random matrix theory. This work quantitatively reproduced the double descent curve in a more generalized setting and precisely calculated the asymptotic expression for generalization error in random feature regression models, theoretically proving that when the signal-to-noise ratio is sufficiently high, optimal generalization performance is achieved by extremely over-parameterized interpolating solutions.

In explaining key mechanisms for achieving benign overfitting, such as implicit regularization, a 2020 study by researchers at the University of Chicago and the Massachusetts Institute of Technology (MIT) analyzed implicit regularization. They pointed out that geometric properties such as high dimensionality, the curvature of the kernel function, and the spectral decay of the data covariance are key factors that contribute to good generalization ability.

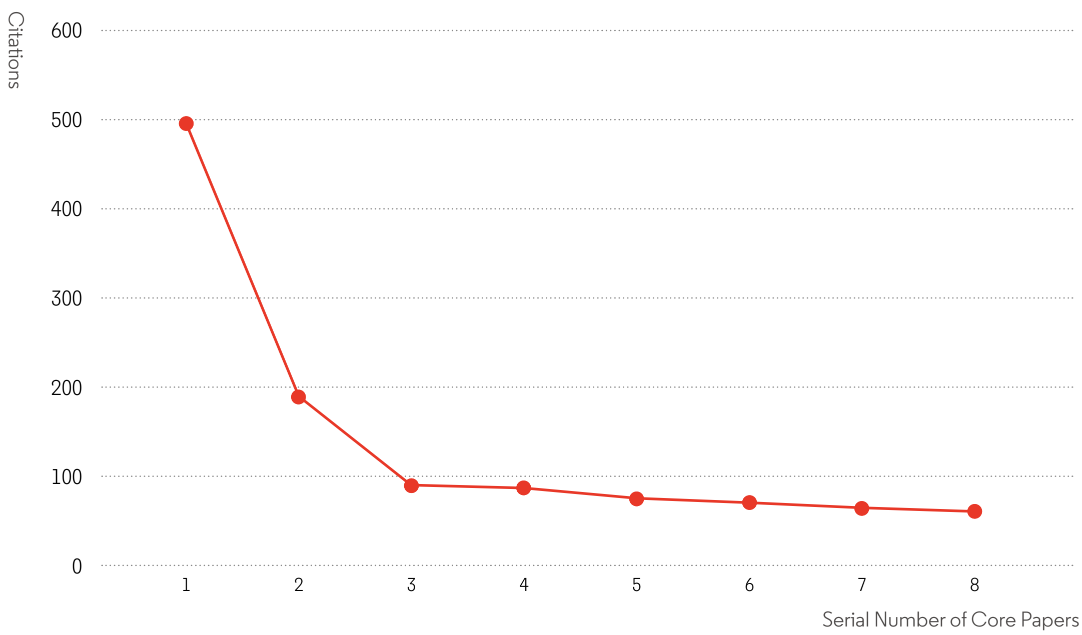
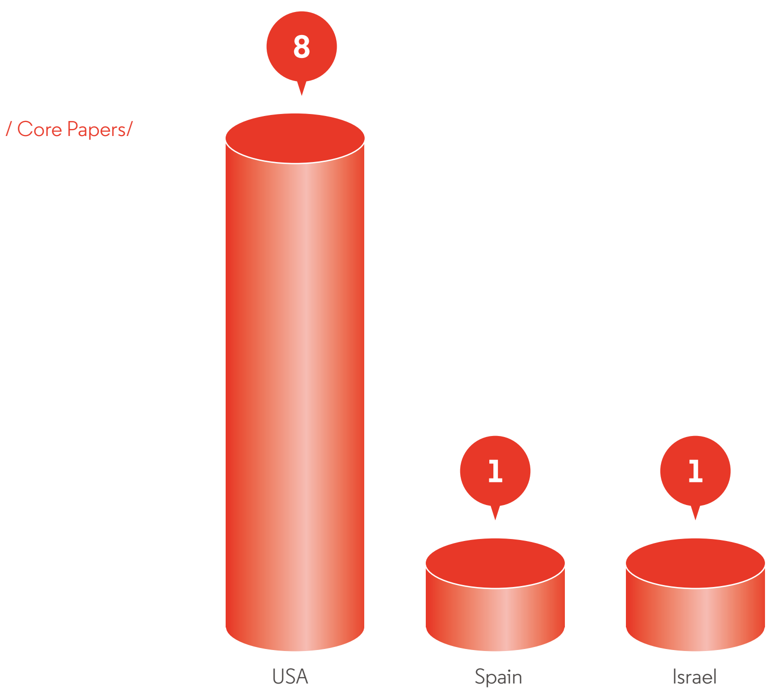


Figure 25: Citation frequency distribution curve of core papers in the Research Front "Double descent curve and generalization phenomena in modern machine learning"

Among the top countries producing core papers (Table 49), the USA participated in all eight core papers, highlighting its absolute leadership in this fundamental research area. Spain and Israel each contributed to one core paper. At the institutional level, the University of California, Berkeley, and Stanford University share the top spot with three core papers apiece. MIT, Columbia University, and the University of California, San Diego, follow closely with two core papers each.

Table 49: Top countries and institutions producing core papers in the Research Front "Double descent curve and generalization phenomena in modern machine learning"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	8	100.0%	1	University of California Berkeley	USA	3	37.5%
2	Spain	1	12.5%	1	Stanford University	USA	3	37.5%
2	Israel	1	12.5%	3	Massachusetts Institute of Technology (MIT)	USA	2	25.0%
				3	Columbia University	USA	2	25.0%
				3	University of California San Diego	USA	2	25.0%
				6	University of Chicago	USA	1	12.5%
				6	Tel Aviv University	Israel	1	12.5%
				6	Pompeu Fabra University	Spain	1	12.5%
				6	Carnegie Mellon University	USA	1	12.5%
				6	Google Inc	USA	1	12.5%
				6	Ohio State University	USA	1	12.5%

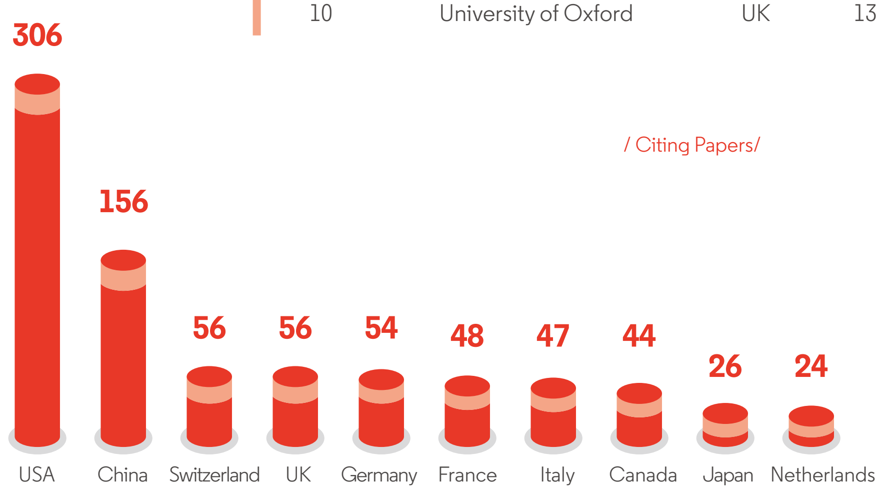


Regarding citing papers, the USA maintains its leading position, with 306 citing papers, accounting for a high proportion of 42.3%. China ranks 2nd with 156 citing papers (21.5%), indicating active follow-up research by Chinese scholars on this disruptive theoretical front. Switzerland and the UK are tied for third, each producing 56 citing papers.

Among the institutions producing citing papers, American universities are dominant. Eight of the top 10 institutions (with 13 institutions tied in total) are based in the USA. Stanford University ranks 1st with 34 citing papers, continuing its leadership in the production of core papers, while the University of California, Berkeley, ranks 3rd. French institutions also performed well, with two in the top rankings: the National Center for Scientific Research of France (CNRS) and Universite PSL rank 2nd and 9th, respectively.

Table 50: Top countries and institutions producing citing papers in the Research Front "Double descent curve and generalization phenomena in modern machine learning"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	306	42.3%	1	Stanford University	USA	34	4.7%
2	China	156	21.5%	2	National Center for Scientific Research of France (CNRS)	France	32	4.4%
3	Switzerland	56	7.7%	3	University of California Berkeley	USA	31	4.3%
3	UK	56	7.7%	4	Swiss federal Institute of Technology in Lausanne	Switzerland	29	4.0%
5	Germany	54	7.5%	5	Harvard University	USA	27	3.7%
6	France	48	6.6%	6	Massachusetts Institute of Technology (MIT)	USA	23	3.2%
7	Italy	47	6.5%	7	University of Pennsylvania	USA	18	2.5%
8	Canada	44	6.1%	8	Columbia University	USA	15	2.1%
9	Japan	26	3.6%	9	Universite PSL	France	14	1.9%
10	Netherlands	24	3.3%	10	Swiss Federal Institute of Technology Zurich	Switzerland	13	1.8%
				10	Princeton University	USA	13	1.8%
				10	University of California San Diego	USA	13	1.8%
				10	University of Oxford	UK	13	1.8%



1.3 KEY HOT RESEARCH FRONT — "Methods and applications of physics-informed neural networks in solving partial differential equations"

Physics-informed neural networks (PINN) are a class of deep learning methods that embed physical laws into the neural network training process. Their core idea is based on using physical constraints described by known partial differential equations (PDE) to guide neural networks in automatically satisfying these constraints when predicting and fitting data.

Since the establishment of calculus by Newton and Leibniz in the 17th century, PDE has served for centuries in providing the mathematical tools to describe the evolution of physical systems such as continuum dynamics, heat conduction, quantum mechanics, and fluid dynamics. The numerical solutions of PDE have progressed through stages, including finite difference methods, finite element methods, and spectral methods. However, with advances in computing power and data science, traditional grid-based numerical methods have shown limitations in solving high-dimensional complex systems, addressing inverse problems, and integrating noisy data.

In 2024, the Nobel Prize in Physics was awarded to John J. Hopfield and Geoffrey E. Hinton, recognizing their fundamental achievements in the fields of artificial neural networks and machine learning, thereby providing a theoretical and methodological foundation for introducing deep learning techniques into scientific computing, especially the value of PINN in solving PDE. PINN is designed to tightly couple neural networks with physical equations, achieving efficient function approximation in continuous space-time domains while simultaneously handling high-dimensional, multi-physics fields and complex boundary condition problems, thereby creating a new paradigm for traditional scientific computing.

This Research Front contains four core papers, with research focusing on using PINN to solve PDE forward problem and inverse problem. Notable progress has been made, particularly in hidden physics identification and data-driven model discovery. The core breakthroughs cover two types of models: continuous-time models serving as data-efficient spatiotemporal function approximators, while discrete-time models, based on high-order implicit Rung-Kutta methods, can achieve high-precision temporal integration. Studies show that PINNs have broad applicability in fields such as fluid mechanics, reaction-diffusion systems, nonlinear shallow-water wave propagation, and quantum mechanics. Hidden Fluid Mechanics (HFM) framework, by embedding Navier-Stokes equations into neural networks, can extract velocity and pressure distribution from flow images while remaining robust under low resolution and noisy data.

Meanwhile, training efficiency has been significantly improved by combining PINNs with the residual-based adaptive refinement (RAR) method, and the DeepXDE library has been developed to implement forward and inverse problem-solving on complex geometric domains, providing practical tools for both scientific research and education.

Future directions include further improving training efficiency for high-dimensional complex systems, designing network structures that automatically satisfy physical invariants, combining multimodal experimental data for implicit physics discovery, and extending to coupled multiphysics and real-time prediction in engineering applications. Overall, this Research Front not only demonstrates the deep integration of deep learning with PDE solution methods but also accelerates the development of scientific machine learning (SciML) in both theoretical research and engineering applications.

In a noteworthy achievement, George Karniadakis, a Fellow of the National Academy of Engineering and professor in the Department of Applied Mathematics at Brown University, participated in all four core papers. Karniadakis has received honors for his contributions to PINN and PDE, including the Computational Fluid Dynamics Award, the J. Tinsley Oden Medal from the US Association in Computational Mechanics, the SIAM/ACM Prize in Computational Science and Engineering, and the G. I. Taylor Medal from the Society of Engineering Science.

Among the four core papers, the most-cited report (with more than 5,300 citations at this writing) was published in the *Journal of Computational Physics*, one of the top international journals in computational mechanics. This paper proposes a physics-informed neural network in which PDEs are directly embedded into the neural network loss function, automatically satisfying physical constraints during the training process. Both continuous-time and discrete-time models are designed by the authors to balance data distribution and temporal integration precision. The former provides efficient spatiotemporal function approximation, whereas the latter supports implicit Runge-Kutta integration of arbitrary order. The effectiveness of PINNs has been verified in solving forward and inverse problems, as well as in handling high-dimensional multi-physics problems in fluid mechanics, quantum mechanics, reaction-diffusion systems, and nonlinear shallow-water waves, thus providing key tools for advancing SciML in engineering and physics applications.

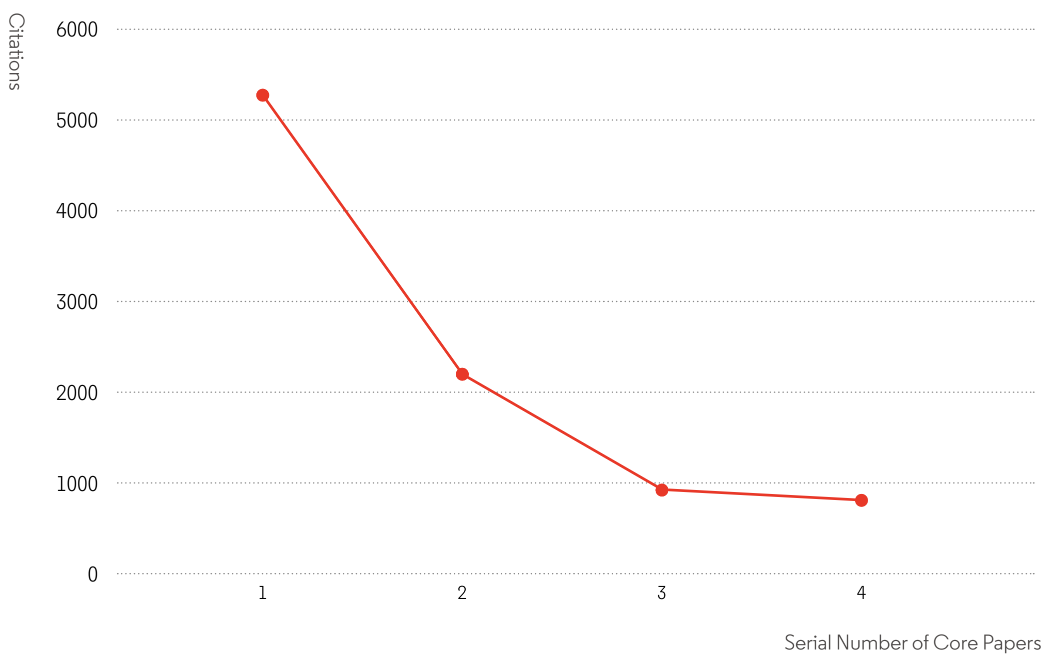


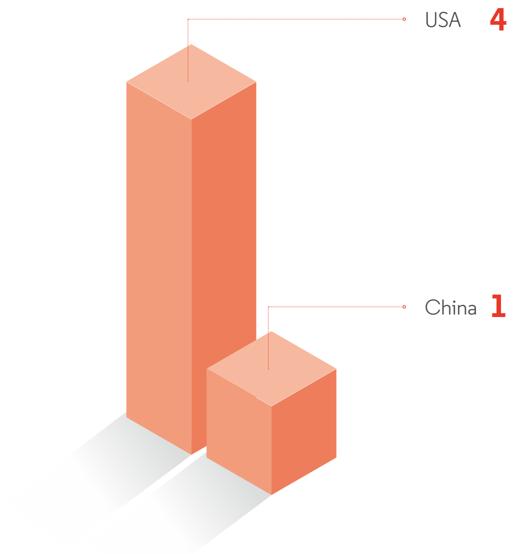
Figure 26: Citation frequency distribution curve of core papers in the Research Front "Methods and applications of physics-informed neural networks in solving partial differential equations"

Examining the distribution of countries and institutions producing the core papers for this front (Table 51) demonstrates that the USA leads, contributing all four core papers, with China participating in one of the foundational reports. At the institutional level, several American institutions are active, with Brown University producing four core papers, and the University of Pennsylvania and the Massachusetts Institute of Technology each contributing two. Additionally, Johns Hopkins University, Pacific Northwest National Laboratory, NVIDIA Corporation, and the University of Colorado Boulder in the USA, as well as Xiamen University in China, each contributed one core paper.

Table 51: Top countries and institutions producing core papers in the Research Front "Methods and applications of physics-informed neural networks in solving partial differential equations"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	4	100.0%	1	Brown University	USA	4	100.0%
2	China	1	25.0%	2	University of Pennsylvania	USA	2	50.0%
				2	Massachusetts Institute of Technology (MIT)	USA	2	50.0%
				4	Johns Hopkins University	USA	1	25.0%
				4	Pacific Northwest National Laboratory	USA	1	25.0%
				4	Xiamen University	China	1	25.0%
				4	NVIDIA Corporation	USA	1	25.0%
				4	University of Colorado Boulder	USA	1	25.0%

/ Core Papers/

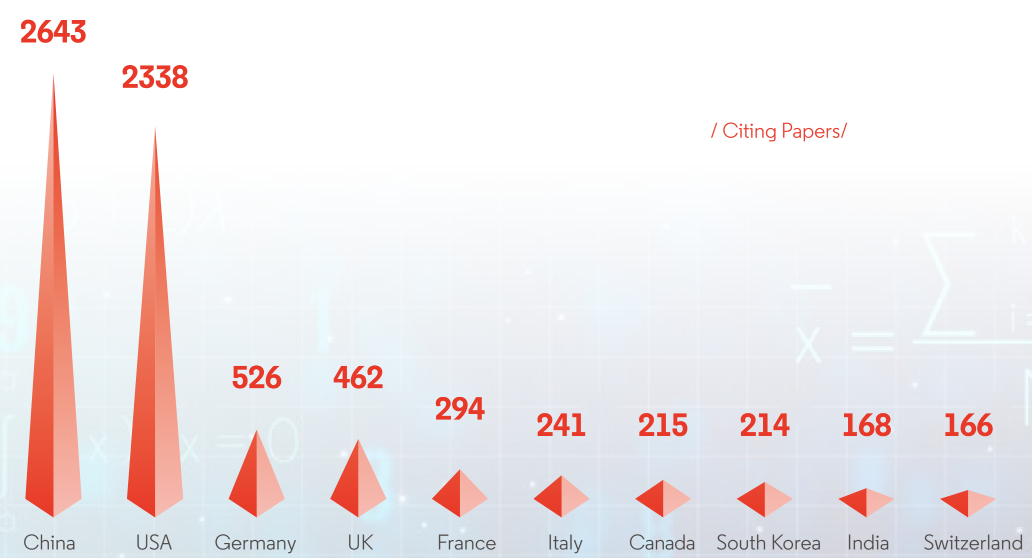


In terms of the citing papers (Table 52), China is the most active country in tracking and advancing research in this area, producing 2,643 citing papers, accounting for 39.3% of the total. The USA ranks 2nd with 2,338 citing papers (34.8%). By comparison with these two nations, other countries have much lower citing-paper outputs.

Among the top institutions producing citing papers, China can claim the most institutions on the list, with five. The Chinese Academy of Sciences ranks 1st and is the only institution with more than 200 citing papers. Tsinghua University, Peking University, Zhejiang University, and Shanghai Jiao Tong University also perform well. The USA has four institutions on the list: Brown University, the Massachusetts Institute of Technology, Stanford University, and Purdue University. France has one institution on the list, the French National Centre for Scientific Research, contributing 176 citing papers, a count second only to the Chinese Academy of Sciences.

Table 52: Top countries and institutions producing citing papers in the Research Front "Methods and applications of physics-informed neural networks in solving partial differential equations"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	2643	39.3%	1	Chinese Academy of Sciences	China	259	3.9%
2	USA	2338	34.8%	2	National Center for Scientific Research of France (CNRS)	France	176	2.6%
3	Germany	526	7.8%	3	Brown University	USA	145	2.2%
4	UK	462	6.9%	4	Tsinghua University	China	143	2.1%
5	France	294	4.4%	5	Massachusetts Institute of Technology (MIT)	USA	140	2.1%
6	Italy	241	3.6%	6	Peking University	China	130	1.9%
7	Canada	215	3.2%	7	Zhejiang University	China	126	1.9%
8	South Korea	214	3.2%	8	Shanghai Jiao Tong University	China	120	1.8%
9	India	168	2.5%	9	Stanford University	USA	116	1.7%
10	Switzerland	166	2.5%	10	Purdue University	USA	102	1.5%



2025
RESEARCH FRONTS

11

INFORMATION SCIENCE

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 five areas: computer vision and 3D perception; next-generation communication and networks; artificial intelligence (AI) for science; medical image computing; and cryptography and security (Table 53). All four hot fronts in computer vision and 3D perception are appearing on this annual list for the first time, including "Research on multimodal 3D real-time object detection for intelligent driving scenarios", "6D object pose estimation and tracking technology", "Generation and detection of neural rendering and deepfakes", and "Voice-driven 3D facial animation and synchronization technology".

Two hot fronts center on next-generation communication and networks. "Research on deep learning-based 6G semantic communication systems" has emerged as a hot front for the first time, while "Design and performance optimization of integrated sensing and communications systems" represents an extension of last year's research on "Integrated sensing and communications", with the focus shifting from theoretical exploration to practical system design and optimization.

Two hot fronts derive from AI for scientific applications. Among them, "Optimizing molecular representation learning via graph neural networks and related techniques" has entered the list for the first time, while "Language model-based protein structure prediction" is related to last year's theme of machine learning-assisted directed protein evolution, with the technical approach shifting from machine learning to language models. Additionally, two other hot fronts have emerged for the first time: "Research on multimodal medical image segmentation and feature extraction" in medical image computing, and "Zero-knowledge proofs: privacy, scalability, and cryptographic applications" in cryptography and security.

Table 53 Top 10 Research Fronts in information science

Rank	Hot Research Fronts	Core papers	Citations	Mean Year of Core Papers
1	Research on multimodal 3D real-time object detection for intelligent driving scenarios	30	3157	2022.3
2	Research on deep learning-based 6G semantic communication systems	26	2343	2022.3
3	Design and performance optimization of integrated sensing and communications systems	32	4814	2022.0
4	Research on multimodal medical image segmentation and feature extraction	18	4995	2021.9
5	Zero-knowledge proofs: privacy, scalability, and cryptographic applications	24	1086	2021.8
6	Voice-driven 3D facial animation and synchronization technology	19	2226	2021.7
7	**6D object pose estimation and tracking technology**	**23**	**1757**	**2021.7**
8	Language model-based protein structure prediction	31	7424	2021.5
9	**Generation and detection of neural rendering and deepfakes**	**20**	**3764**	**2021.3**
10	Optimizing molecular representation learning via graph neural networks and related techniques	6	1873	2021.2

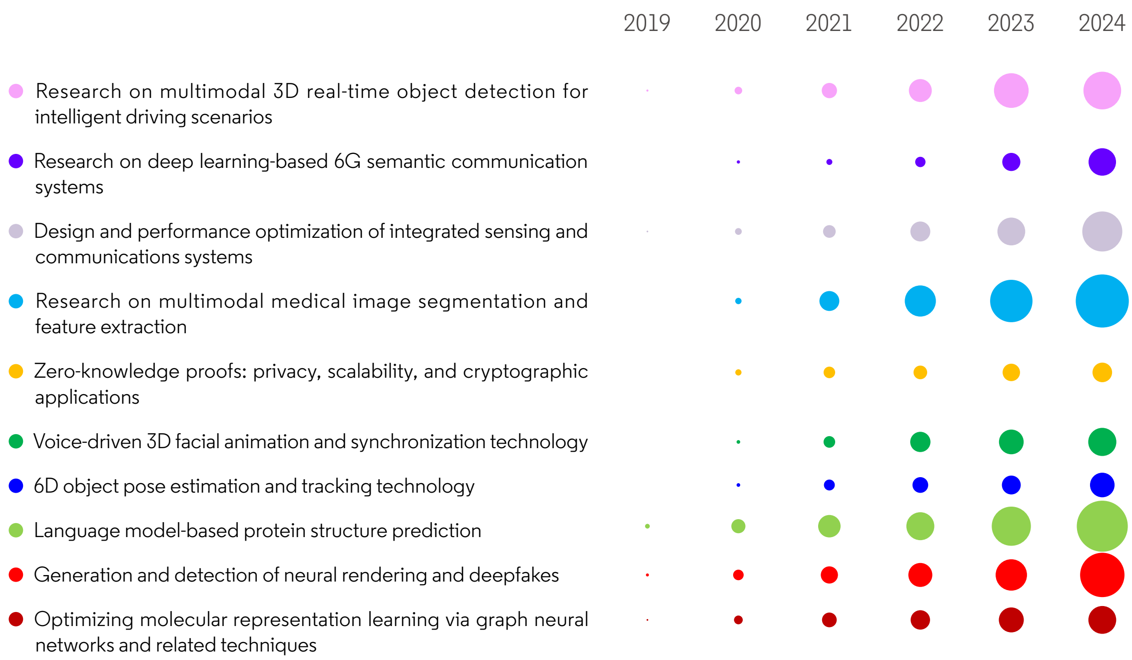


Figure 27 Citing papers for the Top 10 Research Fronts in information science

1.2 KEY HOT RESEARCH FRONT – “6D object pose estimation and tracking technology”

“6D object pose estimation and tracking technology” aims to precisely determine the position (three translational degrees of freedom) and orientation (three rotational degrees of freedom) of target objects in three-dimensional space, and to continuously track their pose changes across consecutive image frames or video streams. This work enables computers to—just like humans—precisely know “where” an object is and “how it is placed” in complex scenarios, while constantly tracking changes in its position and placement angle. This technology has a wide range of applications across various fields.

In the field of industrial robots, this capability can assist robots in accurately grasping and assembling parts, thereby improving production efficiency and product quality. In the field of Augmented Reality (AR), it can achieve precise integration of virtual objects with real scenes, enhancing users’ immersive experience.

With the improvement of computer performance and the emergence of deep learning technology, ongoing work reflected in “6D object pose estimation and tracking technology” will mainly address issues such as occlusion, 3D model-scene integration, dynamic tracking and pose optimization, and cross-modal data fusion. This research will advance toward higher accuracy, increased robustness, and broader application prospects.

This hot Research Front is anchored by 23 core papers. These mainly discuss methods, technological breakthroughs, and practical application support for accurately obtaining the 3D rotation and 3D translation (i.e., 6D pose) of a target from monocular RGB (denoting channels for Red, Green, and Blue) or RGBD images (which add a "Depth" channel). The core papers focus on solving challenges in real-world scenarios such as occlusion, lighting changes, texture loss, and intra-class differences to meet the needs of target spatial positioning in fields like robot operation, autonomous driving, and augmented reality.

Among these foundational reports, the paper "GDR-Net: Geometry-guided direct regression network for monocular 6D object pose estimation," published in the *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* by researchers at Tsinghua University, has the highest citation count, now exceeding 250. This paper proposes an innovative method called GDR-Net (Geometry-Guided Direct Regression Network), which aims to address the core challenges of 6D object pose estimation in monocular RGB images. Targeting the limitations of existing indirect methods (such as PnP/RANSAC) caused by non-end-to-end training, non-differentiability, and time-consuming computation, as well as the insufficient precision of direct regression methods, GDR-Net achieves a breakthrough by integrating a direct regression strategy guided by dense geometric features, laying a foundation for subsequent research in this field.

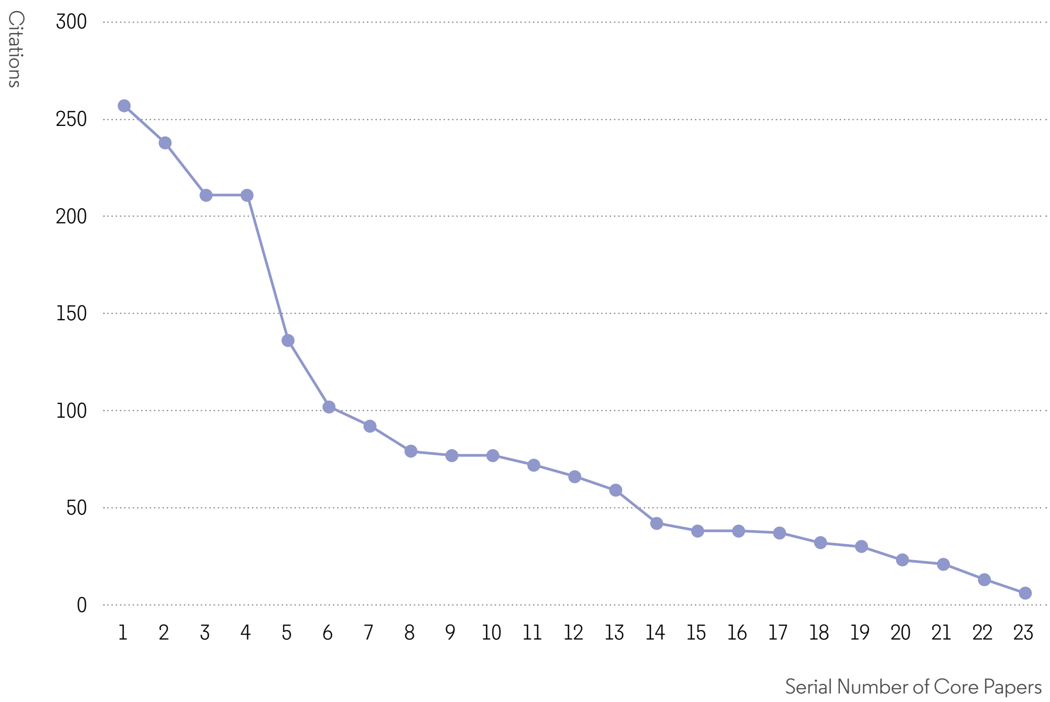


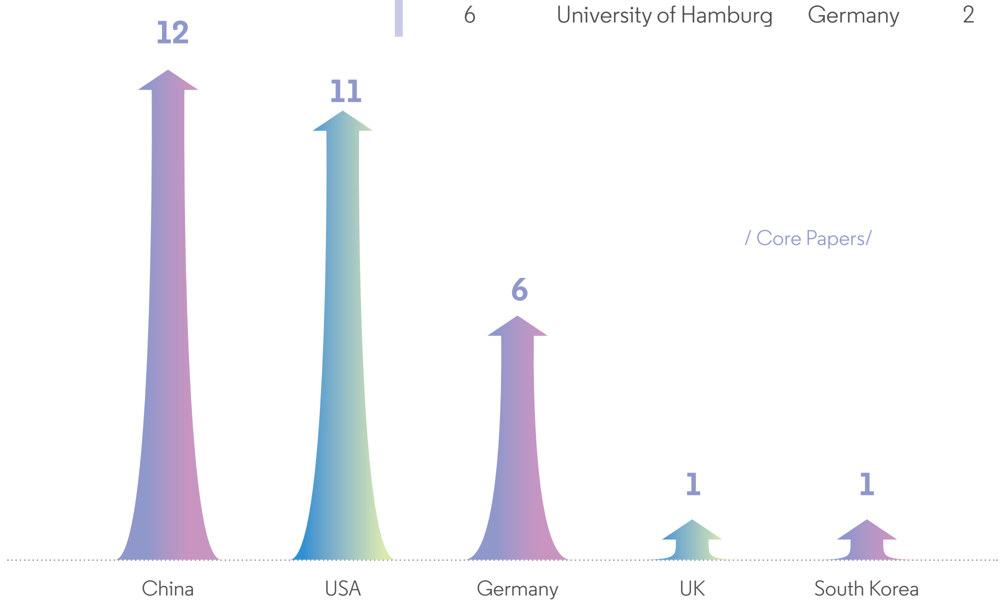
Figure 28: Citation frequency distribution curve of core papers in the Research Front "6D object pose estimation and tracking technology"

Among nations contributing to the 23 core papers in this front, China ranks 1st with 12 papers, accounting for 52.2%, followed closely by the USA with 11 papers, representing 47.8%. These shares reflect the leading positions of both nations in this cutting-edge domain. Germany, ranking 3rd with six core papers, and is also comparatively active.

In terms of institutions producing the core papers, the performance of Tsinghua University is most prominently, ranking 1st with five core papers, accounting for 21.7%. NVIDIA Corporation of the USA contributes four papers, ranking 2nd, demonstrating the important role of corporate entities in this front. Google Inc., Rutgers State University, and the Technical University of Munich, Germany, are tied for third place, each contributing three core papers. Overall, the performance of institutions based in China, the USA, and Germany exhibits markedly different patterns of performance. Universities in China and Germany contribute more than commercial companies in this front, while private enterprise serves as an important research force in the USA.

Table 54: Top countries and institutions producing core papers in the Research Front "6D object pose estimation and tracking technology"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	12	52.2%	1	Tsinghua University	China	5	21.7%
2	USA	11	47.8%	2	NVIDIA Corporation	USA	4	17.4%
3	Germany	6	26.1%	3	Google Inc	USA	3	13.0%
4	UK	1	4.3%	3	Rutgers State University	USA	3	13.0%
4	South Korea	1	4.3%	3	Technical University of Munich	Germany	3	13.0%
				6	Kuaishou Technology	China	2	8.7%
				6	Hong Kong Univ Sci & Technol	China	2	8.7%
				6	Chinese University of Hong Kong	China	2	8.7%
				6	University of Hamburg	Germany	2	8.7%



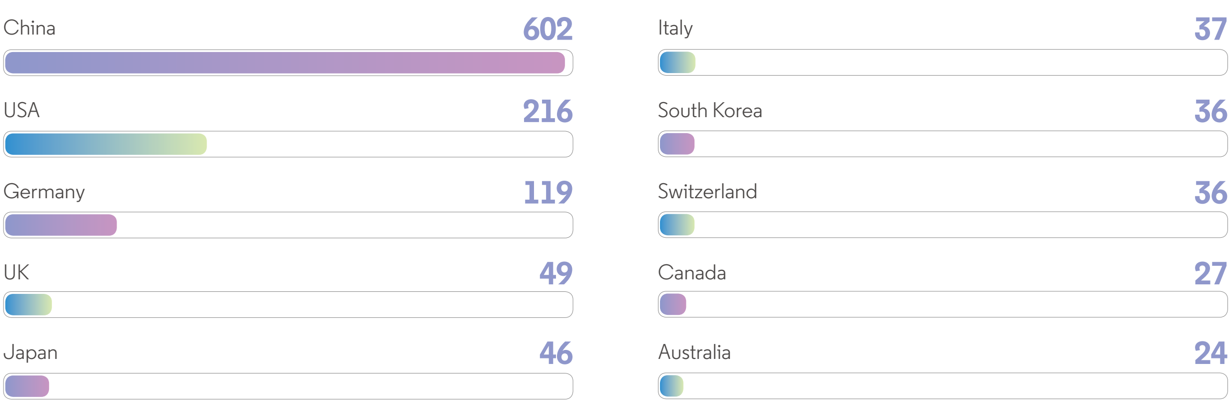
Analysis of the citing papers (Table 55) reveals that China has produced the largest quantity of follow-up research in this front, with more than 600 papers, accounting for 55% of the total. This amply demonstrates the research scale and core influence of China in this specialty area. Secondly, the USA contributed 216 citing papers, accounting for 19.7%. China and the USA strongly drive the further development of this Research Front. Prominent among the next-listed countries are Germany, the UK, and Japan.

In terms of citing institutions, the Technical University of Munich, with 63 citing papers at this writing, accounting for 5.8%, has become the most active research institution in this front. The Chinese Academy of Sciences follows closely in second place with 60 papers, accounting for 5.5%. Tsinghua University, Zhejiang University, and Shanghai Jiao Tong University rank 3rd to 5th respectively. In addition, Beihang University, The Chinese University of Hong Kong, Peking University, and other China-based institutions are also major producers of citing papers in this front.

Table 55: Top countries and institutions producing citing papers in the Research Front "6D object pose estimation and tracking technology"

Country Ranking	country	Citing Papers	proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	proportion
1	China	602	55.0%	1	Technical University of Munich	Germany	63	5.8%
2	USA	216	19.7%	2	Chinese Academy of Sciences	China	60	5.5%
3	Germany	119	10.9%	3	Tsinghua University	China	49	4.5%
4	UK	49	4.5%	4	Zhejiang University	China	43	3.9%
5	Japan	46	4.2%	5	Shanghai Jiao Tong University	China	40	3.7%
6	Italy	37	3.4%	6	Beihang University	China	32	2.9%
7	South Korea	36	3.3%	7	Chinese University of Hong Kong	China	31	2.8%
7	Switzerland	36	3.3%	8	Beijing Institute of Technology	China	23	2.1%
9	Canada	27	2.5%	9	Peking University	China	21	1.9%
10	Australia	24	2.2%	10	Harbin Institute of Technology	China	20	1.8%
				10	Hunan University	China	20	1.8%

/ Citing Papers/



1.3 KEY HOT RESEARCH FRONT – "Generation and detection of neural rendering and deepfakes"

Generation and detection of neural rendering and deepfakes represents a highly challenging leading-edge area in the field of computer vision. On one hand, neural rendering technology, which implicitly represents scenes through neural networks, has achieved unprecedented realism in view synthesis, thereby revolutionizing digital content creation in areas such as film special effects, virtual reality, and autonomous driving simulation—in all, demonstrating significant value applications.

On the other hand, the misuse of these generative technologies can lead to the creation of hyper-realistic forged content, epitomized by deepfakes, posing serious threats to personal privacy, social trust, news authenticity, and national security. Consequently, research advancements in this field exhibit a "offense-defense" dynamic. On the generation side, efforts focus on enhancing rendering speed, fidelity, and efficiency; on the detection side, the aim is to develop more robust forensic algorithms for identifying forgery traces. The parallel progress in these two aspects collectively drives the rapid evolution of both content generation and security authentication technologies.

Twenty core papers underlie this hot Research Front, with seven focusing on neural rendering and 13 on deepfakes and their detection, clearly reflecting the two core aspects of "generation" and "detection" in this field. The papers related to neural rendering introduce methods for neural scene representation and efficient rendering, such as Neural Radiance Fields (NeRF), multi-resolution hash encoding for Instant-NGP, and 3D Gaussian splatting, used for creating highly realistic visual content.

Meanwhile, the deepfake and detection-related papers discuss the broad societal and ethical implications of this technology and propose technical solutions for multimodal, fine-grained forgery detection using advanced deep learning architectures (e.g., spatiotemporal Transformers, multi-scale analysis). Among these, the most-cited paper (with more than 1,000 citations, Figure 29) is "NeRF: Representing Scenes as Neural Radiance Fields for View Synthesis", published in *Communications of the ACM* in 2022. The NeRF method introduced in this paper has revolutionized computer vision by enabling implicit, neural network-based scene representation and novel view synthesis.

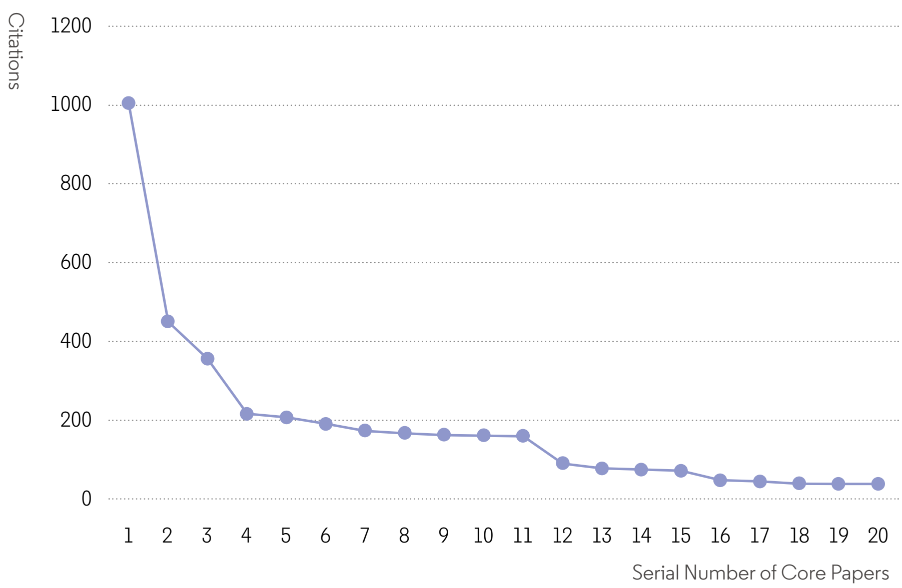
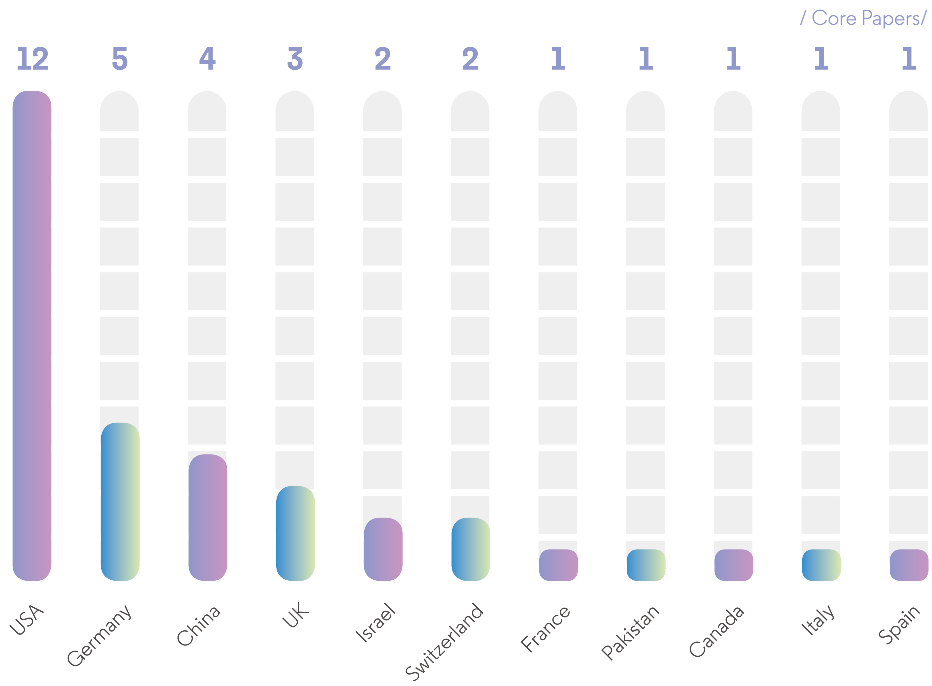


Figure 29: Citation frequency distribution curve of core papers in the Research Front "Generation and detection of neural rendering and deepfakes"

Among the top countries and institutions producing core papers (Table 56), the USA demonstrates the highest contribution, as its 12 papers account for 60% of the total. Although Germany and China rank 2nd and 3rd, respectively, there remains a considerable gap in the number of papers compared to the USA. Among the prolific contributing institutions, the Massachusetts Institute of Technology, the Chinese Academy of Sciences, and the Technical University of Munich each contribute three papers, tying for 1st place. Google, Stanford University, the Max Planck Society in Germany, and two campuses of the University of California also feature on the list, each with two papers. The fact that these institutions are all internationally renowned research universities and organizations underscores the cutting-edge nature of this research topic.

Table 56: Top countries and institutions producing core papers in the Research Front " Generation and detection of neural rendering and deepfakes"

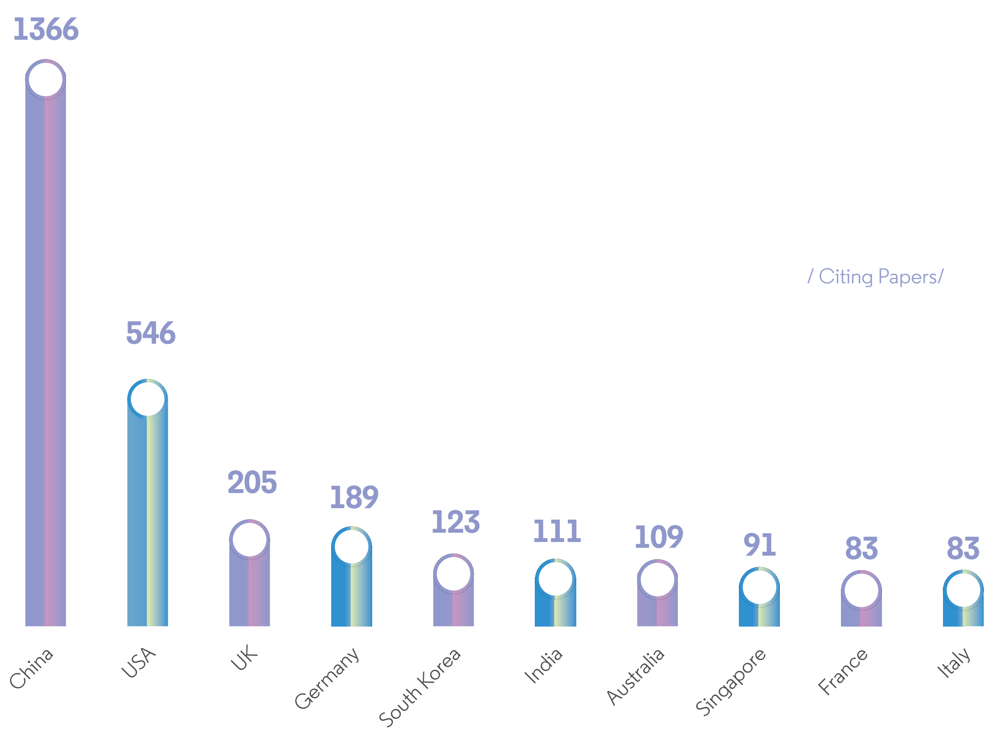
Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	12	60.0%	1	Massachusetts Institute of Technology	USA	3	15.0%
2	Germany	5	25.0%	1	Chinese Academy of Sciences	China	3	15.0%
3	China	4	20.0%	1	Technical University of Munich	Germany	3	15.0%
4	UK	3	15.0%	4	Google Inc	USA	2	10.0%
5	Israel	2	10.0%	4	Stanford University	USA	2	10.0%
5	Switzerland	2	10.0%	4	Max Planck Society	Germany	2	10.0%
7	France	1	5.0%	4	University of California Berkeley	USA	2	10.0%
7	Pakistan	1	5.0%	4	University of California San Diego	USA	2	10.0%
7	Canada	1	5.0%					
7	Italy	1	5.0%					
7	Spain	1	5.0%					



In terms of countries and institutions that cite the core papers in this hot front (Table 57), China stands far ahead of other countries, indicating that the nation continues to maintain robust research activity in this area. The USA ranks 2nd, while the UK and Germany form a third tier by the measure of citing papers. In terms of citing institutions, Chinese entities occupy seven of the top 10 seats, and all of them are well-known universities and research institutions. The Chinese Academy of Sciences ranks 1st with 187 citing papers to date, followed by Tsinghua University, Shanghai Jiao Tong University, and Zhejiang University, which form the second tier in terms of citing papers. The Max Planck Society and Stanford University both feature prominently in core papers and citing papers, demonstrating a sustained output in this research direction.

Table 57: Top countries and institutions producing citing papers in the Research Front " Generation and detection of neural rendering and deepfakes"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1366	51.3%	1	Chinese Academy of Sciences	China	187	7.0%
2	USA	546	20.5%	2	Tsinghua University	China	77	2.9%
3	UK	205	7.7%	3	Shanghai Jiao Tong University	China	70	2.6%
4	Germany	189	7.1%	4	Zhejiang University	China	69	2.6%
5	South Korea	123	4.6%	5	Nanyang Technological University	Singapore	55	2.1%
6	India	111	4.2%	6	Beihang University	China	54	2.0%
7	Australia	109	4.1%	7	Max Planck Society	Germany	46	1.7%
8	Singapore	91	3.4%	8	Stanford University	USA	43	1.6%
9	France	83	3.1%	8	University of Science and Technology of China	China	43	1.6%
9	Italy	83	3.1%	8	Wuhan University	China	43	1.6%



2. EMERGING RESEARCH FRONT

2.1 OVERVIEW OF EMERGING RESEARCH FRONTS IN INFORMATION SCIENCE

“Performance optimization of movable antennas in intelligent wireless communications” was selected as the emerging Research Front in information science for 2025.

Table 58: Emerging Research Front in information science

Rank	Emerging Research Front	Core papers	Citations	Mean Year of Core Papers
1	Performance optimization of movable antennas in intelligent wireless communications	9	265	2023.8

2.2 KEY EMERGING RESARCH FRONT – "Performance optimization of movable antennas in intelligent wireless communications"

Performance optimization of movable antennas in intelligent wireless communications focuses on antennas with adjustable capabilities such as position and angle. This research aims to optimize key aspects of performance, including communication quality, coverage range, and anti-interference ability in intelligent wireless communication. Its applications are extensive and forward-looking.

In the field of intelligent transportation, this performance optimization can be used for dynamic adjustment of vehicle-mounted antennas, enabling high-speed moving vehicles to maintain stable communication with base stations and providing reliable connections for vehicle-road coordination in autonomous driving. In the industrial internet, optimizing the coverage range and signal strength of movable antennas can realize low-latency and high-reliability data transmission for massive devices in factories. In emergency communication scenarios, the attitude of movable antennas can be quickly adjusted to establish temporary communication links, ensuring information exchange at disaster sites.

The research team led by Andrea Goldsmith at Stanford University in the USA has theoretically constructed a channel capacity model for movable antennas. It reveals the quantitative relationship between antenna movement degrees of freedom and communication performance, providing important theoretical support for the design of performance optimization algorithms.

The Huawei corporation has proposed a dynamic adjustment scheme for movable antennas based on intelligent beamforming. By real-time sensing of user positions and channel states, it drives the coordinated optimization of mechanical rotation and electromagnetic parameters of antenna arrays, achieving a communication rate increase of more than 30% in mobile scenarios in 6G test networks.

Currently, this research still faces many challenges. For one, it is difficult to balance the miniaturization and reliability of antenna movement mechanisms, and frequent adjustments are prone to mechanical losses. Secondly, the insufficient accuracy of channel prediction in dynamic scenarios affects the real-time performance of optimization algorithms. Thirdly, the high complexity of multi-antenna coordinated optimization makes it difficult to adapt to large-scale communication networks. In the future, with the in-depth integration of new materials, artificial intelligence, and communication technologies, the performance optimization of movable antennas will move towards a more intelligent, efficient, and reliable direction, providing core technical support for the upgrading of intelligent wireless communications.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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

The top 10 hot Research Fronts in this area show three core trends: 1) The ongoing digital technological revolution is driving socio-economic transformation, reshaping industrial formats, employment, and consumer markets; 2) Sustainable development-related research has emerged as a central theme, focusing on green innovation, climate risks, and energy transition; and 3) Human-health optimization and cognitive management are becoming more technology-based and personalized.

Three hot fronts concern the digital technological revolution and socio-economic transformation, all centered on the technology's empowerment of socio-economic scenarios, which reflects the multidimensional digital reshaping of industry, consumption, and employment. The front on "Research on the Digital Transformation of Cultural and Tourism Industries in the Context of Metaverse" features the application of metaverse and other digital technologies in the study of cultural and tourism industry transformations, while the other two hot fronts—"Robotics Development and Employment Transition" and "Analysis of the Impact of Livestreaming E-commerce Platforms on Consumers"—both focus on the effects of industrial robotics on employment market structure and laborer adaptability.

Four hot Research Fronts concentrate on the area of sustainable development and risk management, forming a complete research chain from green-technology support to market impact and risk control, centering around green development and risk management. Two of these fronts—"Fintech and Green Innovation" and "Energy Transition and Carbon Emission"—integrate financial instruments and transformation strategies with green development goals to provide technological and pathway support for green transition. Research constituting the front on "Market Impacts of Climate Risks and ESG Factors" primarily adopts a market perspective to examine the mechanisms through which climate risks and ESG (environmental, social, and governance) factors affect financial markets and corporate development, linking green development with market feedback. Research in the front "Risk Management Research Based on Quantile Connectivity Analysis" offers technical support for managing and controlling extreme risks in financial markets from the standpoint of methodological innovation.

In the area of human health optimization and cognitive management, three hot Research Fronts have merged, all focusing on technological impacts and health interventions, reflecting the problem orientation approach and humanistic concern of the social sciences. Among them, the front on "Personalized and Data-Driven Psychological Therapy Research" is characterized by the application of big-data technology in the psychotherapy domain to explore personalized intervention models.

The two other fronts—"The Application of Large-Scale Neuroimaging in Research on Individual Behavioral Differences" and "The Expanded Application of Cognitive Load Theory in the Digital Era"—from the perspective of cognitive science, respectively utilize neuroimaging techniques to examine the neural mechanisms of individual behaviors and explore the practical application of cognitive theories in digital contexts. Together, these specialty areas promote the technological and contextual implementation of cognitive management in real-world settings.

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	Research on the digital transformation of cultural and tourism industries in the context of Metaverse	12	1950	2022.4
2	Fintech and green innovation	19	2953	2021.8
3	Robotics development and employment transition	26	4250	2021.7
4	**Personalized and data-driven psychotherapy research**	**19**	**2018**	**2021.7**
5	**Application of Large-Scale Neuroimaging in research on individual behavioral differences**	**7**	**1673**	**2021.7**
6	Energy Transition and Carbon Emission	25	6198	2021.6
7	Risk management research based on quantile connectivity analysis	5	1035	2021.6
8	Market impacts of climate risks and ESG factors	34	7349	2021.4
9	Expanded application of Cognitive Load Theory in the Digital Era	6	991	2021.3
10	Analysis of the impact of livestreaming E-commerce platforms on consumers	22	3940	2021.1

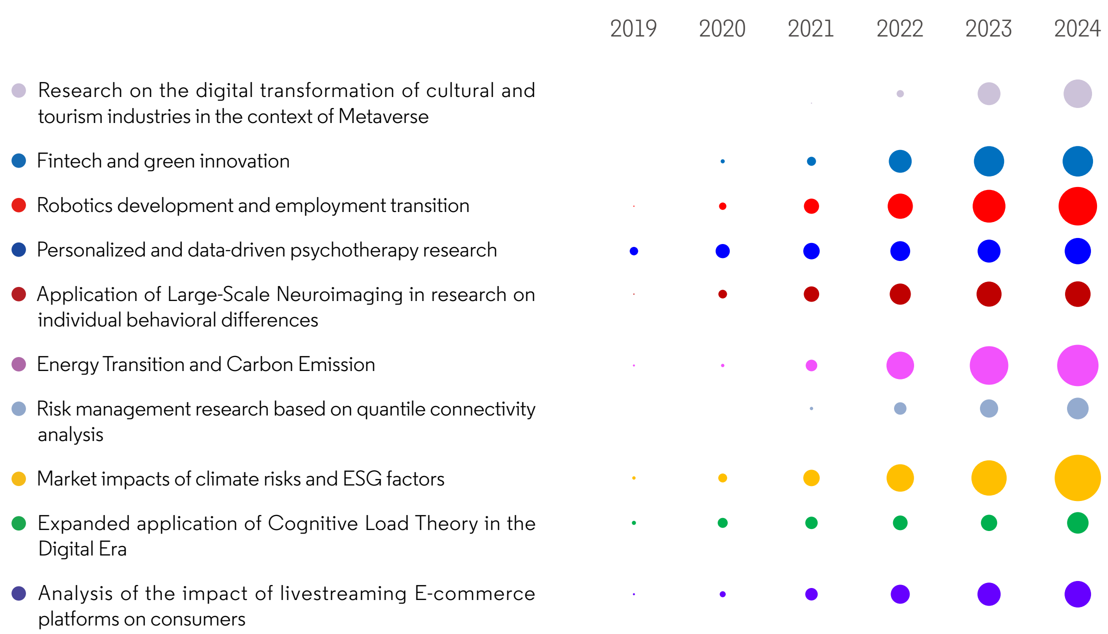


Figure 29: Citing papers for the Top 10 Research Fronts in economics, psychology and other social sciences

1.2 KEY HOT RESEARCH FRONTS---"Robotics development and employment transition"

Ever since the English economist John Maynard Keynes raised concerns about "technological unemployment" in the early 20th century, the issue of whether automation will massively replace human labor has remained a central concern in economics. On the one hand, robots have directly replaced many jobs previously held by humans (the substitution effect); on the other hand, falling production cost and improved efficiency may also generate new labor demand (the productivity effect). As a new round of technological revolution and a wave of industrial transformation takes hold, robots—which stand as a typical representative of advanced manufacturing technologies—are making an extensive penetration into the global manufacturing domain at an unprecedented pace.

As a result, the front on "Robotics development and employment transition" has once again attracted many scholars to undertake in-depth analysis in multiple dimensions, covering technological evolution, employment structural changes, skill alignment of workers, and changes in socio-economic development.

This hot front is identified by 26 core papers. Among them, 18 focus on the impact of employment market structure, covering changes in industry job offers and employment shifts among workers with different skill sets, among other topics. Meanwhile, eight papers examine the application of industrial robots and the green development of industries, examining aspects such as production efficiency, energy consumption, and production-process optimization.

The core's most-cited paper is co-authored by Daron Acemoglu, a Nobel laureate in economics at MIT, and Pascual Restrepo of Boston University. The paper was published in the *Journal of Political Economy* and has been cited more than 960 times to date. Based on Commuting Zone-level data, the authors combine the penetration rate of industry robots with local employment distribution to formulate a Bartik-style exposure index and use it to empirically test the negative impact of robots on employment and wages.

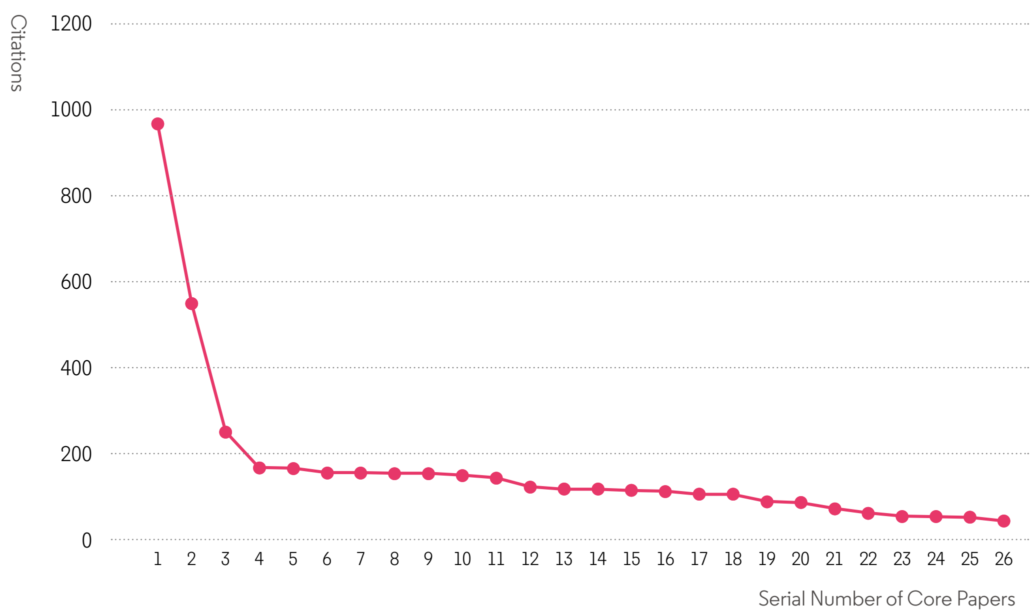
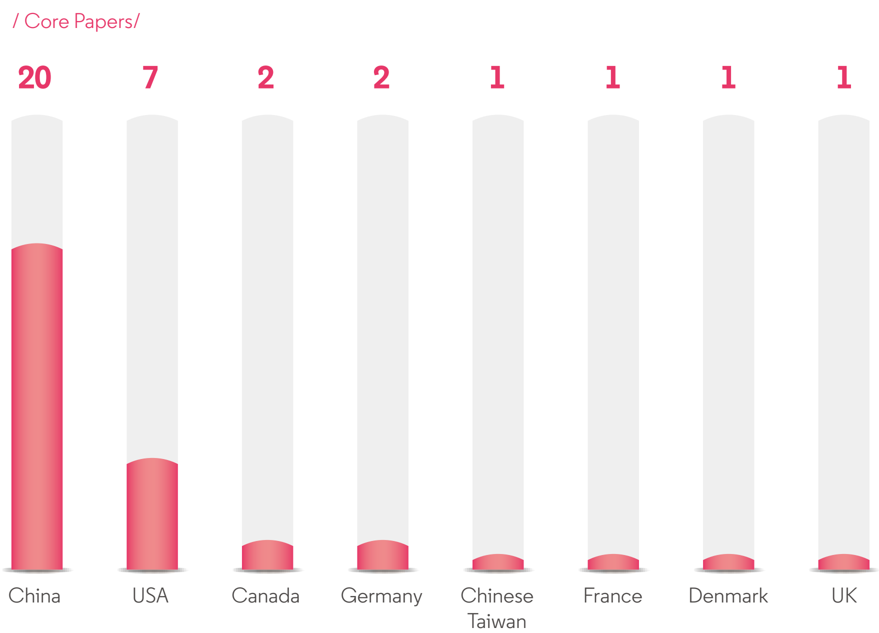


Figure 30: Distribution curve of citation frequency of core papers in the Research Front "Robotics development and employment transition"

In terms of the countries/regions that are most active in producing core papers (Table 57), China ranks 1st, with 20 foundational reports, accounting for 76.9% of the total. The USA is also active in this front. Among institutions, Nanchang University emerges as the most outstanding performer, contributing nine core papers, which account for 34.6%. In addition, MIT, Boston University, and Jiangsu University have each published three core papers in this front.

Table 57: Top countries/regions and institutions producing core papers in the Research Front "Robotics development and employment transition"

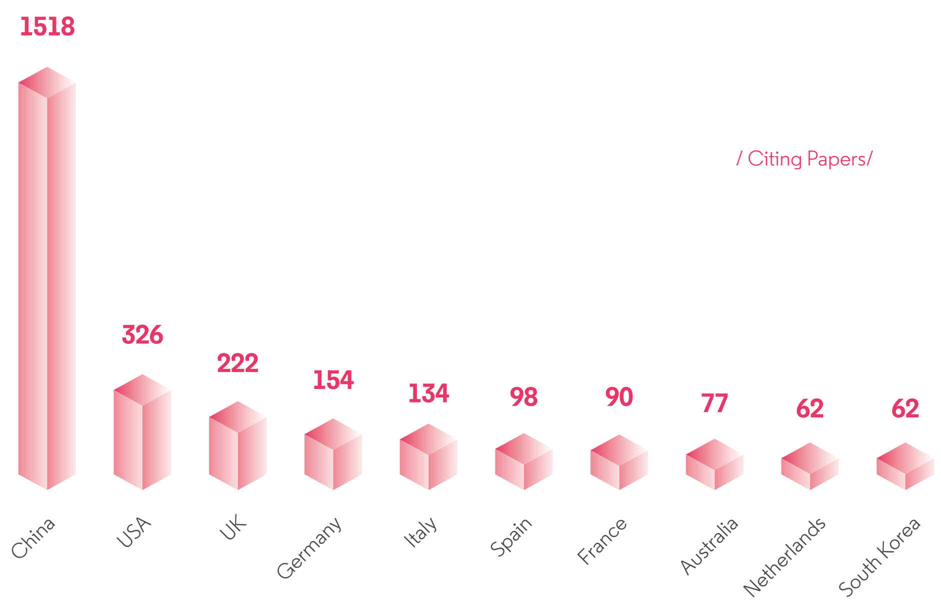
Country/ Region Ranking	Country/ Region	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	China	20	76.9%	1	Nanchang University	China	9	34.6%
2	USA	7	26.9%	2	Massachusetts Institute of Technology (MIT)	USA	3	11.5%
3	Canada	2	7.7%	2	Boston University	USA	3	11.5%
3	Germany	2	7.7%	2	Jiangsu University	China	3	11.5%
5	Chinese Taiwan	1	3.8%	5	Hefei University of Technology	China	2	7.7%
5	France	1	3.8%	5	Southwestern University of Finance and Economics	China	2	7.7%
5	Denmark	1	3.8%	5	Nanjing University of Information Science & Technology	China	2	7.7%
5	UK	1	3.8%	5	Nanjing Audit University	China	2	7.7%
				5	Nanchang Institute of Technology	China	2	7.7%
				5	Wuhan University	China	2	7.7%



In terms of papers that cite the core literature in this front, China is far ahead of other countries, with 1,518 citing papers, accounting for 60.3% of the total and reflecting a high level of attention to this research direction. The USA comes 2nd, with 326 citing papers, accounting for 13%, followed by the UK and Germany which claim 3rd and 4th place, respectively. Countries such as Italy, Spain, and France have also produced significant numbers of citing papers, demonstrating the global academic attention that this hot front has received. Among the top institutions that produce citing papers (including 11 tied institutions), eight are from China, with Nanchang University—ranked 1st in core paper contributions—also being the largest contributor in terms of citing papers. Germany's Institute for the Study of Labor comes 6th, and the Lebanese American University is tied for the 8th place.

Table 58 : Top countries and institutions producing citing papers in the Research Front "Robotics Development and Employment Transition"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	China	1518	60.3%	1	Nanchang University	China	150	6.0%
2	USA	326	13.0%	2	Southwestern University of Finance and Economics	China	52	2.1%
3	UK	222	8.8%	3	Xiamen University	China	46	1.8%
4	Germany	154	6.1%	4	Xian Jiaotong University	China	43	1.7%
5	Italy	134	5.3%	5	Sichuan University	China	40	1.6%
6	Spain	98	3.9%	6	Institute for the Study of Labor	Germany	39	1.6%
7	France	90	3.6%	7	Peking University	China	38	1.5%
8	Australia	77	3.1%	8	Central University of Finance and Economics	China	37	1.5%
9	Netherlands	62	2.5%	8	Hunan University	China	37	1.5%
9	South Korea	62	2.5%	8	Lebanese American University	Lebanon	37	1.5%



1.3 KEY HOT RESEARCH FRONT - "Personalized and data-driven psychotherapy research"

With social development and the improvement of living standards, individuals' growing demand for personalized services has escalated. In the field of psychotherapy, an increasing number of people seek customized psychological support tailored to their individual characteristics to better address their mental-health issues. Unsurprisingly, this development has driven the development of research on personalized psychotherapy.

Meanwhile, the rapid development of data-driven technologies such as big data, artificial intelligence (AI), and machine learning provides powerful tools for psychotherapy research, enabling more efficient collection, processing, and analysis of massive psychological data. In turn, these tools have elucidated underlying patterns in human behavior and psychology, thereby achieving more precise personalized treatment. For this reason, "Personalized and data-driven psychotherapy" has attracted increasing attention and research.

This hot Research Front records a total of 19 core papers, which focus on theoretical innovation, methodological optimization, and practical applications in psychotherapy, reflecting the core trend of today's personalized, data-driven, and evidence-based treatments. Among these core papers, 12 studies concern theoretical and practical studies on Process-Based Therapy and Acceptance and Commitment Therapy (ACT), including the most cited paper in this front, "The future of intervention science: Process-based therapy," now cited more than 430 times. Co-authored by S. G. Hofmann, former President of the American Association for Behavioral and Cognitive Therapies (ABCT), and S. C. Hayes, Co-Founder of the American Academy of Cognitive Therapy (ACT), the paper was published in *Clinical Psychological Science*. This study reveals that future psychological intervention science will focus on the core trend of being "process-based", emphasizing that treatment needs to be combined with individual psychological mechanisms and dynamic change processes rather than merely relying on any fixed treatment mode.

In addition, a total of seven core papers reflect data-driven and measurement-oriented treatment optimization research, focusing on the application value of measurement-based care, routine outcome monitoring (ROM), and progress feedback.

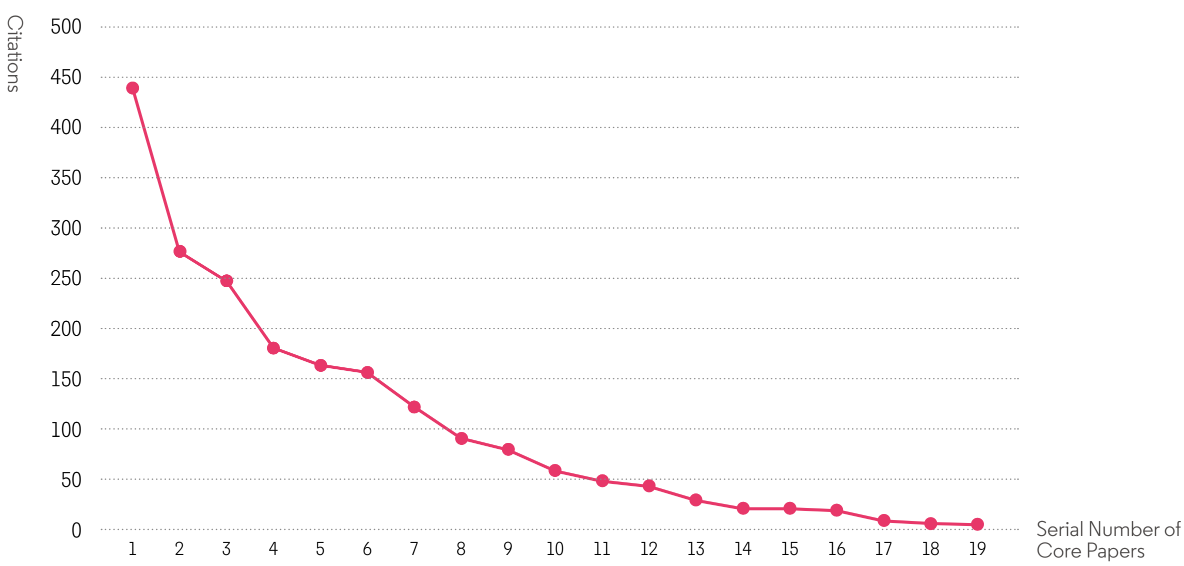


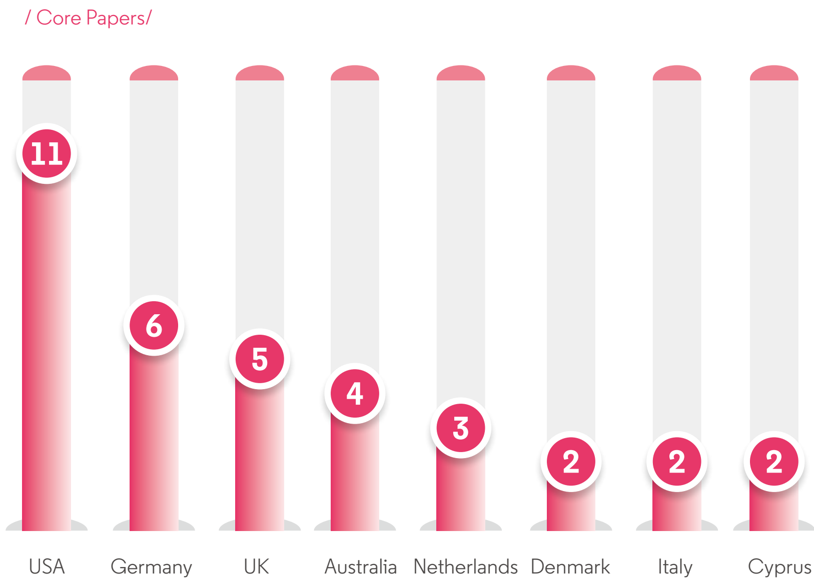
Figure 31 Citation frequency distribution curve of core papers in the Research Front "Personalized and Data-Driven Psychotherapy"

In terms of the top-producing countries for core papers, the USA contributes 11, accounting for 57.9% of the total. This makes the USA the largest producer of core papers in this front, closely followed by Germany (6 papers, 31.6%), the UK (5 papers, 26.3%), and Australia (4 papers, 21.1%). These countries form the central research force in this area.

Countries such as the Netherlands, Denmark, Italy, and Cyprus have also produced important outputs, reflecting a pattern of wide international research in this specialty. In the list of top institutions producing core papers (Table 59), four are based in the USA, with the University of Nevada, Reno, being the top performer, contributing six core papers. Institutions in countries such as Australia, the UK, Germany, the Netherlands, and Cyprus have also made their corresponding contributions.

Table 59: Top countries and institutions producing core papers in the Research Front "Personalized and data-driven psychotherapy research"

Country Ranking	Country	Core Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Core Papers	Proportion
1	USA	11	57.9%	1	University of Nevada	USA	6	31.6%
2	Germany	6	31.6%	2	Australian Catholic University	Australia	4	21.1%
3	UK	5	26.3%	2	University of Sheffield	UK	4	21.1%
4	Australia	4	21.1%	2	Boston University	USA	4	21.1%
5	Netherlands	3	15.8%	5	Philipps-University Marburg	Germany	3	15.8%
6	Denmark	2	10.5%	5	Utah State University	USA	3	15.8%
6	Italy	2	10.5%	5	University of Trier	Germany	3	15.8%
6	Cyprus	2	10.5%	5	Leiden University	Netherlands	3	15.8%
				9	Vanderbilt University	USA	2	10.5%
				9	University of Cyprus	Cyprus	2	10.5%

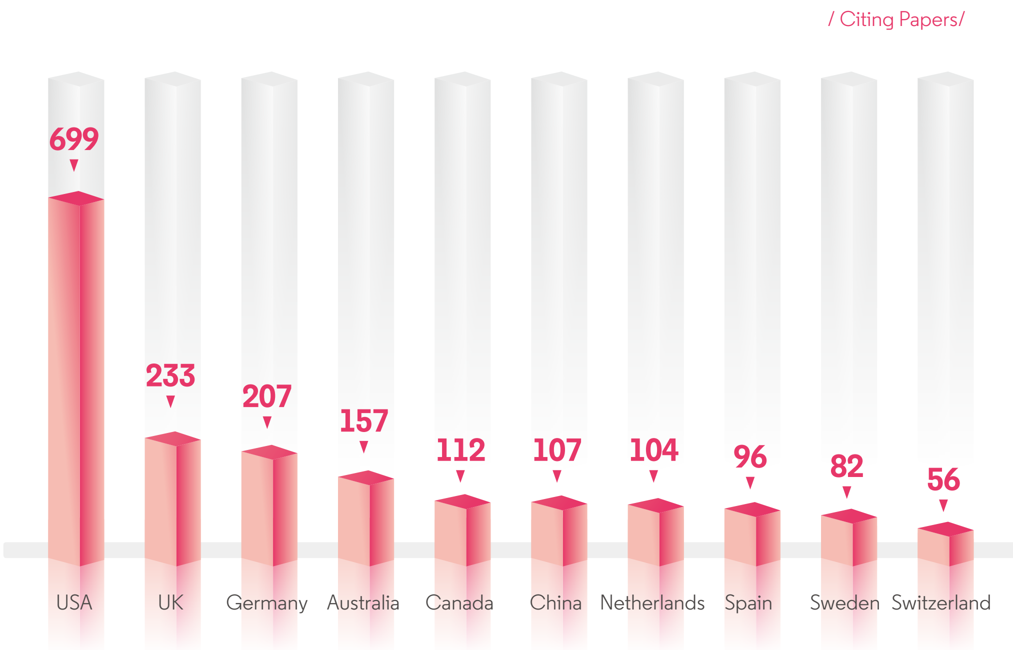


In terms of citing papers, the USA ranks 1st, with 699 citing papers contributing 45% of the total. The UK (233 papers, 15%), Germany (207 papers, 13.3%), and Australia (157 papers, 10.1%) come 2nd, 3rd, and 4th respectively. China ranks 6th, with 107 citing papers and accounting for 6.9%.

Among the Top 10 institutions ranked by citing papers, six are in the USA, with Harvard University (74 citing papers) ranking first by this measure. The University of Trier is 2nd, with Philipps-University Marburg, the University of Nevada, Reno, and Utah State University tied for the 3rd place.

Table 60: Top countries and institutions producing citing papers in the Research Front "Personalized and data-driven psychotherapy research"

Country Ranking	Country	Citing Papers	Proportion	Institution Ranking	Institution	Affiliated Country	Citing Papers	Proportion
1	USA	699	45.0%	1	Harvard University	USA	74	4.8%
2	UK	233	15.0%	2	University of Trier	Germany	51	3.3%
3	Germany	207	13.3%	3	Philipps-University Marburg	Germany	46	3.0%
4	Australia	157	10.1%	3	University of Nevada	USA	46	3.0%
5	Canada	112	7.2%	3	Utah State University	USA	46	3.0%
6	China	107	6.9%	6	Uppsala University	Sweden	45	2.9%
7	Netherlands	104	6.7%	7	Yale University	USA	44	2.8%
8	Spain	96	6.2%	8	Boston University	USA	40	2.6%
9	Sweden	82	5.3%	9	Kings College London	UK	37	2.4%
10	Switzerland	56	3.6%	10	University of Washington	USA	35	2.3%



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: "Application practice and risk management of generative AI in the business domain". Some key interpretations of this front are given below.

Table 64: 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 practice and risk management of generative AI in the business domain	8	166	2023.8

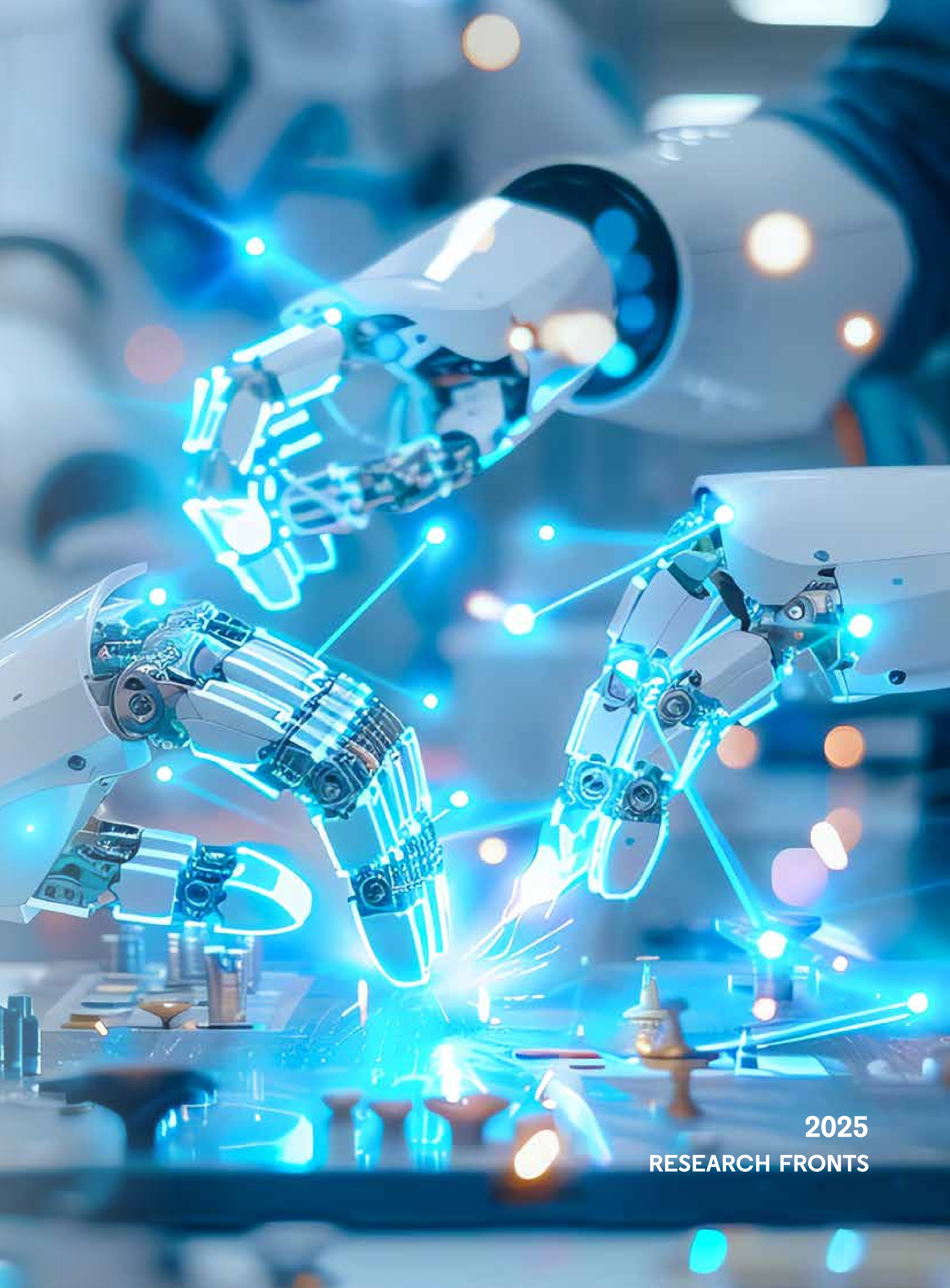
2.2 KEY EMERGING RESEARCH FRONT – "Application practice and risk management of generative AI in the business domain"

With the rapid iteration of AI technologies, generative AI is increasingly permeating the business sector, becoming a core force driving industrial transformation. With its remarkable capabilities in efficient content generation, intelligent interaction and knowledge integration, generative AI has sparked transformative changes in brand building, customer service, innovative R&D, and other scenarios. For instance, generative chatbots based on large language models and deep learning algorithms now can not only make quick responses to user needs and optimize service processes, but also create differentiated competitive advantages and push for the intelligent transformation of traditional business models. Against this backdrop, researchers are proactively tapping into the potential of generative AI in enhancing operational efficiency and fostering human-machine collaboration, while keeping a closer watch on cognitive risks and ethical issues that may arise from the application of generative AI.

Relevant research can be broadly categorized into two directions. One consists of research to explore pathways for practicing AI in various scenarios from a technical application perspective, including leveraging generative AI to establish brand competitive advantages, optimize customer service systems, and formulate efficient innovation strategies. Examples include research on enhancing human-machine co-creation of knowledge through improved AI prompts, innovating operational models in the knowledge industry with conversational AI, or using generative AI as an auxiliary tool to provide diversified solutions for clients.

The other main direction features research examining the potential challenges of technological applications from a risk-management perspective, including how to address the cognitive risks and paradoxes arising from generative AI. These include cognitive bias risks caused by AI-generated "machine nonsense", the efficiency-experience imbalance paradox in AI-enabled customer services, the difficulty of information authenticity verification in the technological application process, and the ambiguity in defining knowledge ownerships and responsibilities in human-machine collaboration.

The application and impact of generative AI technology in the business domain is a research theme that holds enormous potential while also presenting huge challenges. Although generative AI is a powerful tool for enhancing business efficiency and driving industrial innovation, with broad prospects for application in areas such as brand building, customer service, and knowledge management, it is undeniable that the technology still has limitations in terms of cognitive risk control, the delineation of ethical boundaries, and the creation of standards for technical application. All these issues require continued joint explorations by academia and industry.



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APPENDIX

RESEARCH FRONTS: IN SEARCH OF THE STRUCTURE OF SCIENCE

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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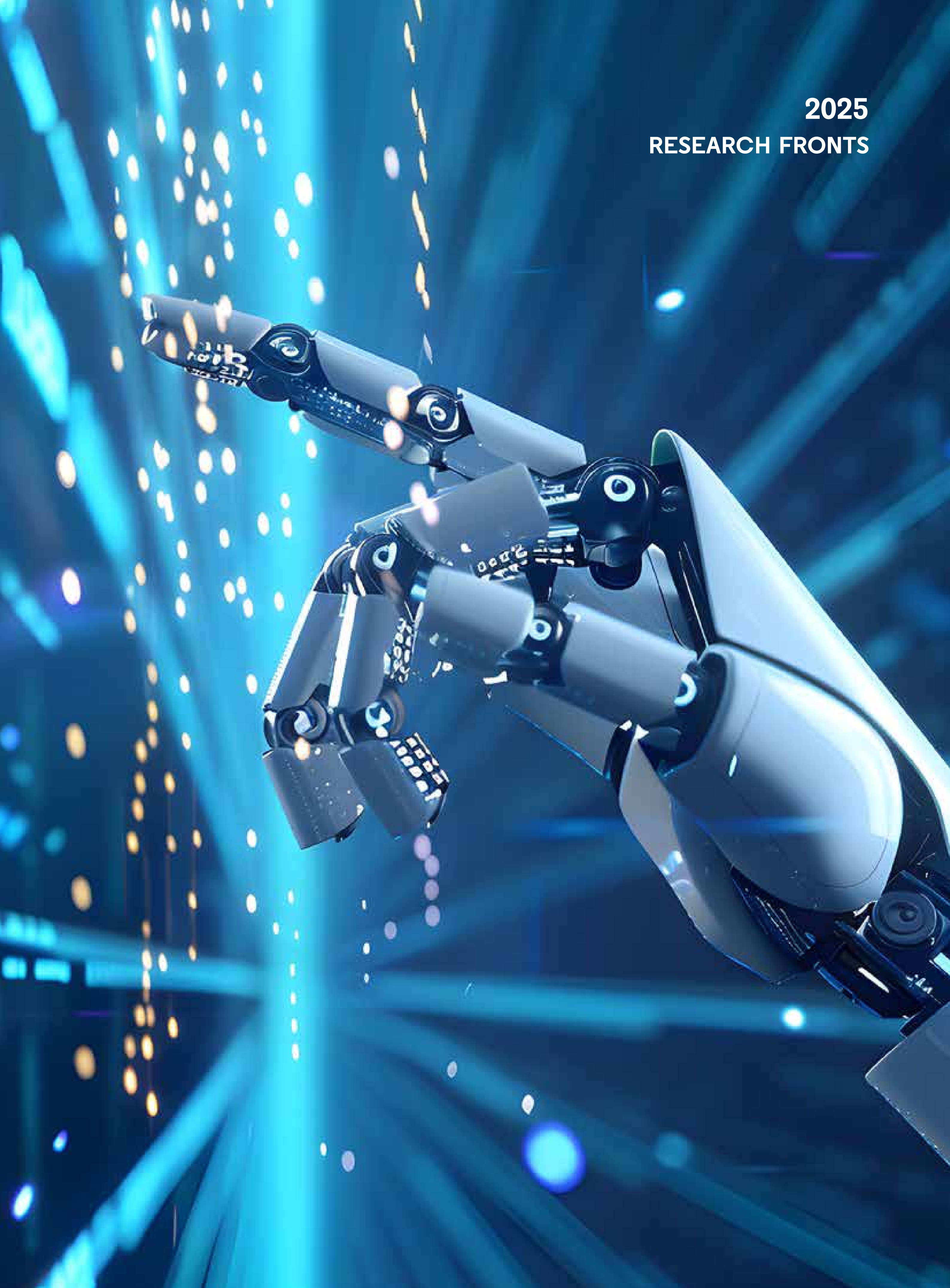

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