

Engineering Fronts 2024

Project Group of Global Engineering Fronts of
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Foreword

Engineering science and technology is an important force to change the world, and engineering fronts represent important directions for the future innovation of engineering science and technology. Currently, changes of the world, of our times and of history are unfolding in ways like never before. The new round of scientific and technological revolution and industrial transformation continue to deepen. Human society is facing unprecedented challenges. It has become the common choice of all countries to keep abreast of the trends in world science and technology, accurately identify changes, respond to them scientifically, and proactively seek changes.

To track the development trend of engineering science and technology, the Chinese Academy of Engineering (CAE), the highest honorary and advisory academic institution in China, has been organizing a project known as “Global Engineering Fronts” every year since 2017. The research identifies and releases nearly two hundreds of engineering research fronts and engineering development fronts every year to guide academic development and promote the innovation of engineering science and technology.

The 2024 Global Engineering Fronts research relies on nine academic divisions and academic journals of the CAE to identify 92 engineering research fronts and 92 engineering development fronts. This is done by paying equal attention to the engineering research and development fronts, integrating quantitative analysis and qualitative research, and combining data mining and expert argumentation. Among these, 29 key engineering research fronts and 29 key engineering development fronts are selected for detailed interpretations.

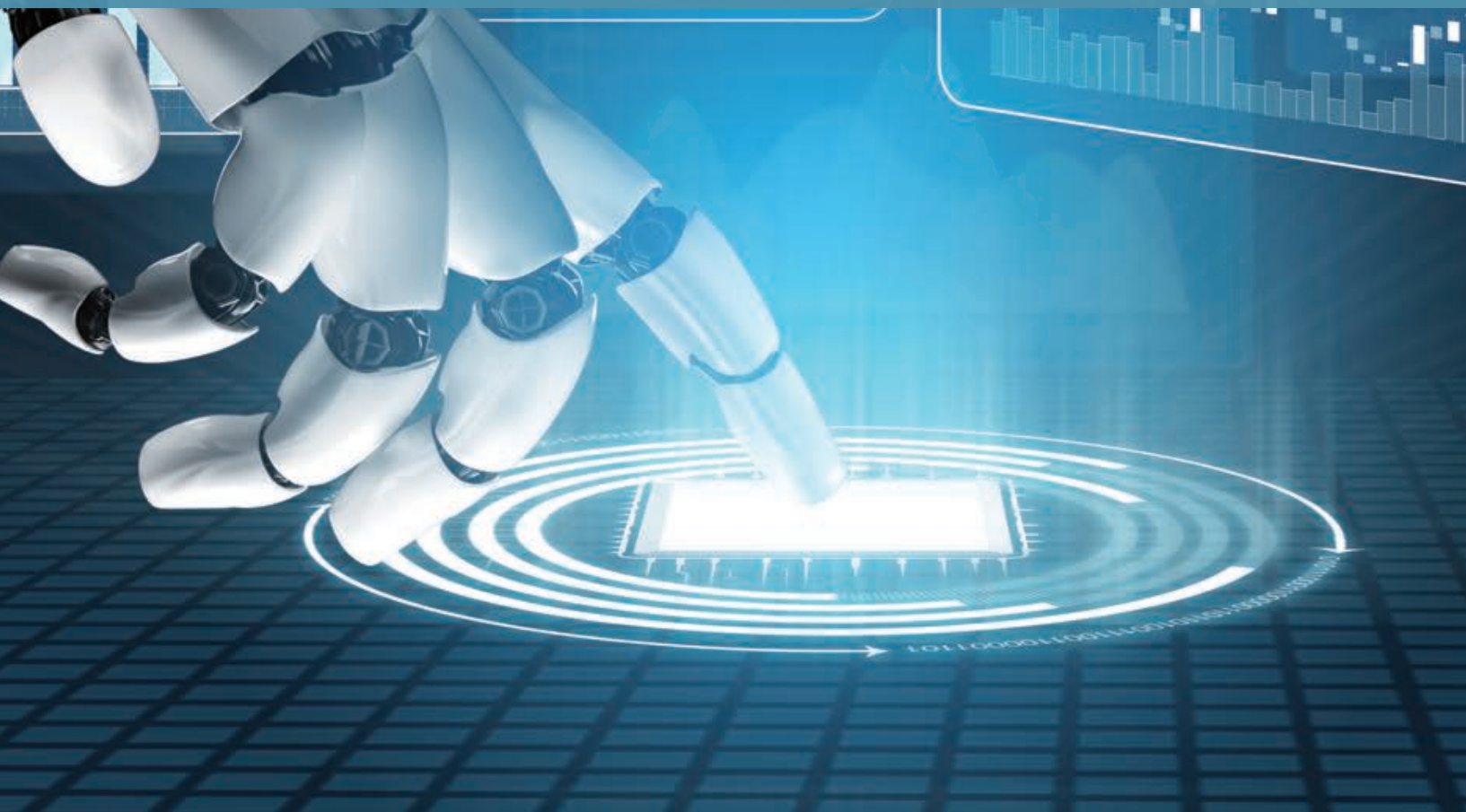
In 2024, we continued to improve the technical system at the initial stage of the project to define the technology boundary and structure of the nine fields and sort out the correlation among the branches of technology. In the process of key engineering fronts interpretation, the development roadmap tool was used to study the development directions of key engineering fronts in the next 5–10 years.

This report presents the results of the 2024 project and comprises two parts. Chapter 1 explains the data and methodology. Chapter 2–10 present the technology reports focusing on nine fields: (i) mechanical and vehicle engineering; (ii) information and electronic engineering; (iii) chemical, metallurgical, and materials engineering; (iv) energy and mining engineering; (v) civil, hydraulic, and architectural engineering; (vi) environmental and light textile engineering; (vii) agriculture; (viii) medicine and health; (ix) engineering management. Each report describes and analyzes the engineering research and development fronts in the respective field and explains the key fronts in detail.

Identifying engineering fronts is a complex and challenging task. For eight years, the research team has been focusing on the development hotspots and challenges of the global engineering science and technology and gradually explored a unique research path, that is, the research, forums, and journals were closely integrated to promote each other. The project was supported by nearly a thousand of academicians and experts from various fields and institutions. We are grateful to all of them!



Chapter 1 Methodology



Engineering is the practical activity in which human beings transform the world with the help of science and technology. An engineering front refers to the key direction that is forward looking, leading, and exploratory. It has a major influence and plays a leading role in the future development of engineering science and technology and serves as an important guide for cultivating new quality productive forces. According to the innovation stage of the front, engineering fronts are categorized into engineering research fronts which focuses on the theoretical exploration and engineering development fronts which focuses on the practical application of engineering science and technology.

The Global Engineering Fronts 2024 project has adopted multi-round interactions between experts and data for iterative research and analysis, realizing a deep integration of judgments of experts and data analyses. In 2024, 92 global engineering research fronts and 92 global engineering development fronts are selected, with 29 engineering research fronts and 29 engineering development fronts being listed as the key focus of interpretation. The distribution of engineering research and engineering development fronts among the nine fields is shown in Table 1.1.

The research of fronts consists of three stages: data preparation, data analysis, and expert review. In the data preparation stage, the domain, library, and information experts formulate the literature and patent search strategy according to the technological systems to define the scope of data mining. In the data analysis stage, the co-citation clustering method is used to obtain clustered literature topics and the co-word clustering method to obtain the ThemeScape patent maps. In the expert review stage, the fronts are gradually selected and determined through front topic section, front name revision, expert panel discussions, and other methods. To address the lacking of novelty due to algorithm limitations or lags in data mining, experts from different fields were encouraged to check the results of the data analysis to revise, combine, and expand the engineering fronts. A flowchart of the operation procedure of the Global Engineering Fronts project is illustrated in Figure 1.1, in which the green, purple, and red boxes indicate the data analysis,

Table 1.1 Distribution of engineering research and engineering development fronts among the nine fields

Field	Number of engineering research fronts	Number of engineering development fronts
Mechanical and Vehicle Engineering	10	10
Information and Electronic Engineering	10	10
Chemical, Metallurgical, and Materials Engineering	10	10
Energy and Mining Engineering	12	12
Civil, Hydraulic, and Architectural Engineering	10	10
Environmental and Light Textile Engineering	10	10
Agriculture	10	10
Medicine and Health	10	10
Engineering Management	10	10
Total	92	92

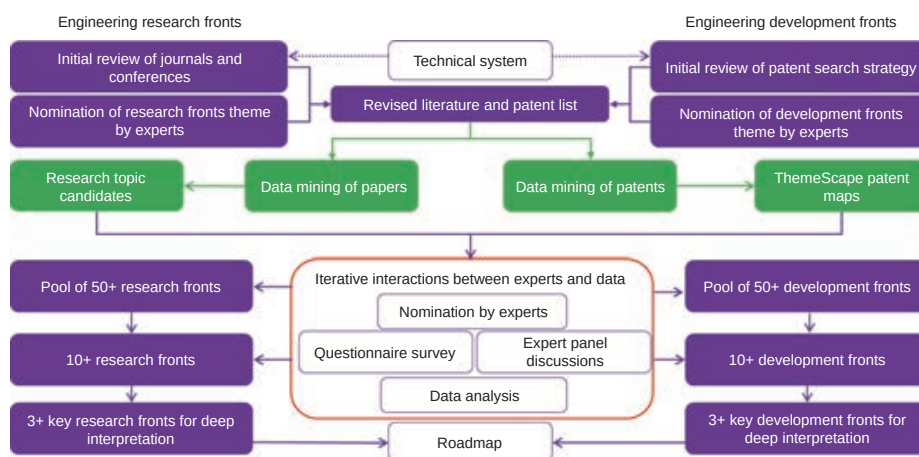


Figure 1.1 Operation procedure of the Global Engineering Fronts project

expert research, and multi-round iterative interactions between experts and data, respectively.

1.1 Identification of engineering research fronts

The identification of the engineering research fronts is performed using two methods. The first approach involves determining the clustered literature topics through the co-citation clustering method according to the SCI journal papers and data of conference proceedings collected from the Web of Science Core Collection. The second method is calling for the engineering research themes through expert nomination. Candidate engineering research fronts that were identified through expert argumentation and refinement went through questionnaire surveys and multiple rounds of expert discussions, yielding 92 engineering research fronts in the nine fields.

1.1.1 Acquisition and preprocessing of paper data

Firstly, the mapping relationship between the technology systems of nine academic divisions of the CAE and Web of Science disciplines was constructed, and the lists of academic journals and conferences corresponding to each field were obtained. After the correction and supplementation by domain experts, the sources for data analysis in the nine fields were determined to be 12 758 journals and 62 407 conferences. In addition, for articles from 82 multidisciplinary sciences journals, the field of each article was reassigned to the most relevant subject area according to the subjects cited in its references.

Accordingly, the articles and conference papers published between 2017 and 2022 were retrieved (the cut-off date of the citations was January 2024). For each field, the differences between journals and conferences, the publication year, and so on were comprehensively considered. By processing journals and conference proceedings separately, high impact papers that are ranked among the top 10% of the citations were selected as the original dataset for the analysis of the research fronts, referring to the highly cited papers in Web of Science, as shown in Table 1.2.

Table 1.2 Overview of data sources in each field

No.	Field	Number of journals	Number of conferences	Number of high-impact papers
1	Mechanical and Vehicle Engineering	550	3 669	118 453
2	Information and Electronic Engineering	1 013	26 833	234 742
3	Chemical, Metallurgical, and Materials Engineering	1 242	5 258	324 743
4	Energy and Mining Engineering	950	3 076	167 219
5	Civil, Hydraulic, and Architectural Engineering	398	1 666	108 120
6	Environmental and Light Textile Engineering	1 372	1 765	261 369
7	Agriculture	1 492	1 468	201 850
8	Medicine and Health	4 909	16 860	532 119
9	Engineering Management	832	1 812	64 041

1.1.2 Mining of clustered literature topics

Through the co-citation clustering analysis of the high-impact papers in the aforementioned nine data datasets, all the clustered

literature topics in the nine fields were obtained and each clustered topic consists of a certain amount of core papers. The topics of the journal and conference papers published during 2018–2021 were selected according to the number of core papers, total number of citations, mean publication year, and proportion of consistently cited papers. Consequently, 35 diverse literature topics were extracted. The topics of the journal and conference papers published during 2022–2023 were selected according to the number of core papers, total number of citations, and proportion of consistently cited papers. Thereafter, 25 different clustered literature topics were obtained. Overlapping topics were replaced by topics that did not intersect with other fields. In addition, subjects that were not covered by clustered topics were extracted separately by keywords. Finally, 734 clustered literature topics in the nine fields were obtained (Table 1.3).

Table 1.3 Statistics of co-citation clustering results in each field

No.	Field	Number of clustered topics	Number of core papers	Number of candidate research hotspots
1	Mechanical and Vehicle Engineering	12 459	49 999	100
2	Information and Electronic Engineering	22 820	100 842	71
3	Chemical, Metallurgical, and Materials Engineering	30 028	122 356	63
4	Energy and Mining Engineering	16 846	70 664	87
5	Civil, Hydraulic, and Architectural Engineering	11 160	46 162	117
6	Environmental and Light Textile Engineering	25 695	102 451	90
7	Agriculture	19 546	75 991	78
8	Medicine and Health	50 251	209 881	64
9	Engineering Management	6 176	23 543	64

1.1.3 Determination and interpretation of research fronts

While processing and mining the paper data, domain experts put forward research front issues via a comprehensive analysis of data pertaining to science and technology news and policies, and integrated them into each stage of front determination.

In the data preparation stage, the library and information experts transform the front research issues raised by domain experts into search strategies, which are an important part of the initial data source. In the data analysis stage, for subjects that are not covered by clustered literature topics, domain experts provide keywords, representative papers, or representative journals for customized search and mining. In the expert review stage, domain experts will check for omissions based on the clustered literature results and conduct the second round of nomination for fronts that do not exist in the data mining results but are considered important. Library and information experts provide data support. Finally, the domain experts merge, revise, and refine the engineering research front topics obtained through data mining and expert nomination. Subsequent to questionnaire surveys and multiple rounds of conference discussions, approximately 10 engineering research fronts were selected for each field.

In each field, three or four key research fronts were selected according to the development prospects and the significance. Authoritative experts in the front direction were invited to interpret the fronts in detail from the perspectives of national and institutional layout, cooperation networks, development trends, and R&D priorities.

1.2 Identification of engineering development fronts

The identification of the engineering development fronts is primarily performed using two methods. First, based on the Derwent

Innovation patent database, the top 10 000 patent families of 53 subjects in the nine fields with highest citations were clustered, and 53 ThemeScape maps were obtained. The domain experts interpreted the candidate engineering development fronts from these maps. The second approach involves nomination by experts. The candidate development fronts obtained through these two methods went through multiple rounds of expert discussion and questionnaire surveys. Consequently, 92 engineering development fronts were identified in total.

1.2.1 Acquisition and preprocessing of patent data

In the data preparation stage, based on the Derwent Innovation patent database, the initial patent data retrieval scope and search strategies for the 53 disciplines of the nine fields were determined using the Derwent World Patents Index (DWPI) Manual Codes, International Patent Classification numbers, United States Patent Classification numbers, and other patent classification numbers and specific technical keywords. Domain experts deleted, supplemented, and improved the patent search strategies to determine the patent retrieval criteria and nominated candidate front topics, which were then transformed into patent search strategies by library and information experts. The above two parts of the search strategies were integrated to determine the patent search strategies of the 53 disciplines, searched in the enhanced patent data—DWPI and Derwent Patent Citation Index (DPCI) collection, and obtained the patent literature of the corresponding disciplines. The retrieved patents were published between 2018 and 2023; the cut-off date of the citations was January 2024. To further concentrate patent literature, the millions of patent documents were screened according to the “annual average number of citations” and “technical coverage width” indicators, thereby obtaining the top 10 000 patent families in each discipline.

1.2.2 Mining of patent topics

Semantic similarity analysis of patent texts were conducted for the top 10 000 highly cited patents on 53 disciplines in the nine fields. Based on literature topic clustering using DWPI titles and abstracts, 53 ThemeScape patent maps were obtained, which effectively display the distribution of the engineering development techniques and show the overall technical information of the collected patents in the form of keywords.

Experts from various fields, with the assistance of library and information experts, selected the engineering development fronts from ThemeScape maps, merged similar fronts, and determined the final development fronts. Finally, they selected the candidate engineering development fronts of each specialty group. To avoid missing emerging or interdisciplinary fronts, domain experts interpreted the data from patents with few citations and poor correlation in the ThemeScape maps.

1.2.3 Determination and interpretation of development fronts

While processing and mining the patent data, domain experts identified issues on development fronts based on a comprehensive analysis of other data, such as science and technology news and policies, and integrated them into each stage of front determination.

In the data preparation stage, the library and information experts transformed the key front issues raised by domain experts into patent search strategies as an important part of the basic dataset. In the data analysis stage, domain experts conducted the second round of front nomination to supplement the emerging technology points that are significant but have been submerged in data mining with few patents. In the expert review stage, domain experts studied highly cited patents, and library and information experts assisted them in interpreting patent maps from multiple perspectives, such as “peaks”, “blue oceans”, and “islands”.

Finally, domain experts merged, revised, and refined the interpreted results of the patent maps and fronts nominated by experts to obtain candidate engineering development fronts, and then selected approximately 10 engineering development fronts in each field through questionnaire surveys or multiple rounds of seminars.

In each field, three or four key development fronts were selected according to the development prospects and the significance. Authoritative experts in the front directions were invited to interpret the fronts in detail from the perspectives of national and institutional layout, cooperation networks, development trends, and R&D priorities.

1.3 Development roadmap

Technology roadmaps are an important tool to depict the development trend of technologies. To strengthen the academic leading role of the engineering fronts, the Global Engineering Fronts 2024 project conducted detailed analysis on the development focuses and trends of three key engineering research fronts and three key engineering development fronts for each field, and drew a development roadmap in a visual way for each front in the next five to ten years.

1.4 Terminologies

Publications/Papers: This includes peer-reviewed and published journal articles, reviews, and conference papers retrieved from Web of Science.

High-impact papers: Papers that are in the top 10% in terms of citation frequency are considered to be of high impact, taking into account the year of publication and journal subject category.

Clustered literature topic: A combination of topics and keywords obtained through a co-citation clustering analysis of high-impact papers.

Core papers: Depending on how the research front is obtained, core papers have two meanings. If it originates from a front that is obtained from data mining and revised by experts, the core paper is considered as a high-impact paper. If it comes from a front nominated by domain experts, the core paper is included in the top 10% of papers in terms of citation frequency obtained using the corresponding search strategy. **Percentage of core papers:** The proportion of core papers in which a country or institution participates among the total number of core papers produced by all countries or institutions.

Citing papers: Collection of papers that have cited core papers.

Citations: The number of times the paper has been cited by the Web of Science Core Collection.

Mean year: Average publication years for all papers among the clustered literature topics.

Consistently cited papers: Papers included in the top 10% in terms of citation velocity.

Citation velocity: An indicator used to measure the growth rate of the cumulative number of citations for a certain period.

In this study, the citation velocity of each paper begins with the month of publication, and the cumulative number of citations per month was recorded.

Highly cited patents: The around top 10 000 DWPI families ranked by the average annual DPCI citations.

Core patents: According to the different ways of obtaining a development front, core patents have two meanings. If they come from the fronts of the patent map, core patents refer to highly cited patents. If they are from the fronts nominated by domain experts, core patents refer to all patents obtained by topic search.

Percentage of published patents: The proportion of core patents in which a country (priority country) or institution participates among the total number of core patents produced by all countries or institutions.

ThemeScape map: A themed landscape representing the overall outlook of a specific industry or technical field. It is a visual presentation in the form of a map obtained by analyzing the semantic similarity of value added DWPI information of patents to gather the patents of related technologies.

Technical coverage width: It is measured by the number of DWPI Classes to which each DWPI patent family covers. This indicator can reflect the breadth of the technology coverage of each patent.

Specialty division criteria system of the academic divisions of the CAE: This is specified in the Specialty Division Criteria of the Academic Divisions of the Chinese Academy of Engineering for Member Election (Trial). It refers to 53 specialized disciplines covered by the nine academic divisions of engineering science and technology, including mechanical and vehicle engineering; information and electronic engineering; chemical, metallurgical, and materials engineering; energy and mining engineering; civil, hydraulic, and architectural engineering; environmental and light textile engineering; agriculture; medicine and health; and engineering management.



Chapter 2 Mechanical and Vehicle Engineering Fronts



2.1 Engineering research fronts

2.1.1 Trends in the Top 10 engineering research fronts

The ten most-researched engineering topics in the field of mechanical and vehicle engineering include mechanical, transportation, ship and marine engineering; weapon science and technology; aeronautical and astronautical science and technology; and power and electrical equipment engineering and technology (Table 2.1). Among these, “ship digital twin system”, “offshore floating solar power generation”, “4D printed shape memory polymers”, “multi-frequency GNSS PPP”, “micro-supercapacitor”, and “triboelectric nanogenerator based on cellulose aerogels” are extensively studied traditional topics. “Scene parsing based on depth images”, “high-speed super-resolution ultrasound imaging”, “phase-change energy storage”, and “composite structures for multi-scale energy absorption” are considered as emerging topics. The annual publication of papers during the years 2018–2023 is listed in Table 2.2.

(1) Ship digital twin system

The ship digital twin system refers to a new type of intelligent ship system based on the digital twin concept. Its core involves building a virtual ship model that synchronously maps to the physical ship. Through the interaction between the physical ship and the virtual model, various applications driven by models and data can be realized. With cross-temporal and spatial characteristics, the ship digital twin system can monitor, analyze, predict, optimize, and control the physical ship quickly, comprehensively, and optimally. Key technologies include comprehensive ship perception, virtual ship model construction and iteration, ship digital twin data processing and management, intelligent ship application development and service, and physical-virtual ship communication and interaction. Current research primarily focuses on digital twin-driven design, construction, fault prediction and health management, and operation management. Emerging technology trends include integration of digital twin-based ship design and construction, physical-virtual fusion testing of ship, precise construction and synchronous evolution of multidisciplinary ship

Table 2.1 Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Ship digital twin system	23	589	25.61	2020.3
2	Offshore floating solar power generation	16	826	51.62	2020.4
3	Scene parsing based on depth images	15	494	32.93	2022.1
4	4D printed shape memory polymers	4	204	51.00	2022.0
5	Multi-frequency GNSS PPP	36	1 608	44.67	2020.7
6	High-speed super-resolution ultrasound imaging	10	1 069	106.90	2019.4
7	Phase-change energy storage	30	1 166	38.87	2021.6
8	Composite structures for multi-scale energy absorption	8	262	32.75	2022.4
9	Micro-supercapacitor	148	31 289	211.41	2019.4
10	Triboelectric nanogenerator based on cellulose aerogels	31	2 708	87.35	2020.6

Table 2.2 Annual number of core papers published for the Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Ship digital twin system	6	2	2	6	6	1
2	Offshore floating solar power generation	2	2	5	2	4	1
3	Scene parsing based on depth images	0	0	1	3	4	7
4	4D printed shape memory polymers	0	0	0	0	4	0
5	Multi-frequency GNSS PPP	0	5	11	9	11	0
6	High-speed super-resolution ultrasound imaging	3	2	3	2	0	0
7	Phase-change energy storage	0	0	3	11	12	4
8	Composite structures for multi-scale energy absorption	0	0	0	0	5	3
9	Micro-supercapacitor	40	44	39	18	5	2
10	Triboelectric nanogenerator based on cellulose aerogels	4	6	5	4	8	4

digital twin models, and the parallel operation and maintenance of ship and shore systems.

(2) Offshore floating solar power generation

Offshore floating solar power generation refers to a floating platform system with photovoltaic (PV) modules that capture and convert solar energy in marine environments. Similar to traditional floating solar power generation, the system consists of a floating structure, PV modules, connectors, mooring systems, anchoring systems, and submarine cables. This floating PV system utilizes water areas, avoiding the use of land resources, and benefits from the cooling effect of water to enhance PV efficiency. However, the harsh marine environment challenges the reliability and durability of the floating PV structure, necessitating optimization and upgrades.

Current research in this field includes ① structural design optimization of offshore floating solar power systems, ② environmental impact assessment of these systems, ③ efficiency improvement, and ④ integration technologies. Future developments involve integrating offshore floating PV with seawater desalination, aquaculture, and hydrogen production and combining it with offshore wind power to create large-scale offshore power stations or energy islands. Technological trends include lightweight and intelligent design of floating platforms, integrated function design, and environmentally friendly design.

(3) Scene parsing based on depth images

Scene parsing based on depth images mainly refers to assigning category labels to each pixel in the image based on the depth image and the corresponding RGB image to achieve a comprehensive analysis of the entire scene. The typical application of this approach lies in the semantic segmentation of road environments in the fields of autonomous driving and robot navigation. Scene parsing methods based only on RGB images often perform poorly in scenes with similar objects or complex backgrounds, while depth images contain additional location and contour information, endowing the algorithm with superior context interpretation capabilities and thereby achieving highly accurate scene parsing.

At present, the main technical directions in this field are mainly centered on neural network structures and learning techniques. The main network structures include pyramid, encoder-decoder, and twin network structures. Commonly used learning techniques include attention mechanisms, deep saliency map-guided segmentation, and the use of cross-modal complementary information and cross-level complementary information. The future development direction of this field focuses on combining the prior knowledge of large visual models with the data advantages of weakly supervised learning. Specific technology development trends include the following: semantic segmentation correction technology based on large visual models, weakly supervised semantic segmentation technology based on prior knowledge, network lightweight technology based on pruning, semantic

segmentation technology based on incremental learning, and video semantic segmentation technology based on time-domain correlation.

(4) 4D printed shape memory polymers

The use of 4D printed shape memory polymers (SMPs) has led to the development of innovative structures that combine 3D printing with smart material technology, enabling shape memory capabilities. These structures can transform their shape, properties, and functions in response to external stimuli such as temperature, light, magnetic fields, electrical currents, and chemical solutions. By leveraging the shape memory effect and adding a time dimension to the 3D printing process, 4D printing enables the printed structures to dynamically adjust and adapt to environmental changes. This adaptability facilitates complex functions such as self-repair, self-assembly, and environmental responsiveness during use. These smart structures are used in aerospace, electronic packaging, smart textiles, soft robotics, and biomedicine.

Current research in this field focuses on the optimization of SMP materials, advancements in 4D printing technology, integration of multifunctional smart structures, development of novel smart structures, and design of contact/non-contact deformation drivers. Recent innovations in smart structures include structures with tunable Poisson's ratios, biomimetic structures inspired by natural organisms, and origami/hinge structures. With advancements in materials science and printing technology, the future development of 4D-printed SMPs is expected to focus on several key areas. These structures combine the programmable deformation advantages of SMP materials with the customizable complex manufacturing capabilities of 3D printing. Key development trends include enhancing SMP materials and structures to achieve high mechanical properties and rapid response times, advancing multi-material co-printing techniques, establishing theoretical models for 4D printing, simulating the deformation of smart structures under multi-physics field coupling, and developing specialized software and hardware for 4D printing.

(5) Multi-frequency GNSS PPP

Multi-frequency global navigation satellite system (GNSS) positioning utilizes navigation signals from multiple frequency bands and satellite systems, including GPS, GLONASS, BeiDou, and Galileo. Precise point positioning (PPP) is the core capability, with top technological levels including real-time kinematic (RTK) and PPP-RTK. Compared with traditional single-satellite positioning systems, multi-frequency GNSS offers better positioning accuracy, stronger anti-interference capabilities, and wider signal coverage. Enhancing capabilities in key areas such as low earth orbit (LEO) constellations, limited ground-based augmentation systems, low-cost terminals, and smart transportation requires the integration of new technologies and addressing of development demands. While, the future complicated application environments require multi-frequency GNSS to enhance capabilities in key areas such as LEO constellations, limited ground-based augmentation systems, low-cost terminals, and smart transportation through the integration of new technologies and addressing development demands.

Currently, the main technological directions in this field include precision positioning for scenarios such as LEO constellation enhancement, limited ground-based enhancement facilities, low-cost application terminals, and seamless indoor and outdoor services. Specific technological trends include fast and precise positioning methods for wide-area sparse ground-based augmentation under large-scale and long baseline constraints, GNSS positioning performance improvement algorithms based on LEO constellation enhancement and complex fragmented observation data, precision positioning algorithms running on low-cost processing platforms that integrate characteristics of operational terminals such as smartphones, and heterogeneous GNSS/multi-sensor data fusion technology for seamless indoor and outdoor positioning coverage.

(6) High-speed super-resolution ultrasound imaging

Ultrasound imaging captures images of the internal composition of the human body or materials by processing reflected ultrasound signals. It possesses excellent spatial resolution (sub-millimeter) and temporal resolution (tens of frames per second), making it widely used in industrial non-destructive testing and clinical disease diagnosis and treatment. However, owing to diffraction effects, the spatial resolution of ultrasound imaging is limited by the ultrasound wavelength. Although increasing the frequency can improve the spatial resolution, it also increases attenuation, inevitably reducing penetration depth.

High-speed super-resolution ultrasound imaging overcomes the traditional diffraction limit. It increases spatial resolution by an order of magnitude while maintaining penetration depth and field of view. This advancement resolves the conflict between resolution and penetration in ultrasound imaging. Current trends in this field include super-resolution imaging with microbubble positioning, super-resolution reconstruction through acoustic structure illumination, atomic force ultrasound microscopy, and metamaterial-based deep subwavelength imaging. Future developments will focus on techniques such as phase-change microbubbles, acoustic structural illumination, wavenumber-domain ultrafast ultrasound imaging, and high-frame-rate ultrasound data acquisition. Specifically, advancements are expected in real-time 3D/4D super-resolution ultrasound imaging and contrast-free super-resolution ultrasound imaging.

(7) Phase-change energy storage

Compared with widely used sensible heat storage methods (e.g., water heat storage, molten salt energy storage, etc.), phase-change energy storage offers high heat storage density and consistent thermal charging and discharging temperatures. This technology has important applications in many fields, including passive thermal protection and thermal management of key electronic devices in military and civilian equipment. In buildings and space habitats, it can maintain or reduce indoor temperature fluctuations and realize energy savings through cold and heat storage. In addition, large-scale phase-change energy storage benefits electric grid and industrial applications by enabling peak shaving and waste heat recovery, which helps achieve the dual carbon goals.

Current research in phase-change energy storage focuses on high-performance materials, long-term cycling stability, and thermal storage and heat exchange systems. Development trends include tuning the phase-change temperature of energy storage materials to fit different applications, aiming for ultra-high heat storage density, low toxicity, and low cost. It also involves cycling stability studies to achieve a long lifespan of phase-change materials in various applications. Enhancing the heat transfer of phase-change materials during charging and discharging is another key focus, along with developing large-scale thermal storage and heat exchange equipment suitable for phase-change materials.

(8) Composite structures for multi-scale energy absorption

Composite structures for multi-scale energy absorption are designed to considerably improve energy dissipation in impact and collision environments through cross-scale material design and structural optimization. It is one of the current focuses in materials science and engineering. This area integrates microscopic material distribution, mesoscopic structural configuration, and macroscopic geometric morphology to create efficient, lightweight energy absorption systems. Current research focuses on the energy consumption mechanism of multi-physical field coupling, functional optimizations of multi-scale materials and structures, and the development and preparations of high-performance composite materials.

The main technical cores of efficient energy absorbing composite structures include high-precision simulation and optimization algorithms, fine-tuning of multi-scale material properties, bio-inspired multi-scale structural designs, multi-level material-structure composite systems, and advanced manufacturing technologies (e.g., nanoscale additive manufacturing, vacuum-assisted technology, etc.). Future developments aim for more intelligent, adaptive, environmentally friendly, and high-efficiency designs, including mechanical metamaterials, adaptive structural designs inspired by biology, intelligent response materials, new high-performance composite materials like nano-enhanced and bio-based materials, and advanced manufacturing technologies. The goal is to maximize energy absorption performance for aerospace, transportation, safety protection, and other fields.

(9) Micro-supercapacitor

Micro-supercapacitors are advanced electrochemical energy storage devices characterized by high power density, integrability, and stability through micro- and nanoscale material and structure design. Compared with traditional batteries, micro-supercapacitors provide the peak power required for fast charging, efficient energy conversion, and long-lasting continuous energy supply, making them ideal for next-generation highly-integrated and miniaturized devices.

Research in this field focuses on designing and preparing high-energy-density electrode materials, exploring large-scale arrayed

electrode preparation methods, optimizing electrode-electrolyte interfaces and electrolytes, enhancing integrated structures, and developing applications for miniaturized devices. The development trend emphasizes multifunctional integrated design to meet miniaturization and integration demands, creating self-powered integrated microsystems, using flexible electrode materials and advanced nanotechnology for flexible and wearable technology applications, and employing machine learning and artificial intelligence (AI) for energy intelligence and autonomous control. Micro-supercapacitors show great potential for applications such as providing peak power for internet of things (IoT) devices, rapid charging of wearable electronics, long-term stable operation of implantable medical devices, and instantaneous energy recovery and assisted acceleration for electric vehicles because of their high power density.

(10) Triboelectric nanogenerator based on cellulose aerogels

Triboelectric nanogenerators can easily convert low-frequency and low-strength mechanical energy into electrical energy and have a simple, reliable structure. They have broad application prospects in energy collection, human-machine interaction, wearable electronics, and medical electronics. However, most current triboelectric nanogenerators are made from traditional polymers and metals, which are not biodegradable and contribute to environmental pollution.

In recent years, degradable and renewable cellulosic materials have attracted much attention. Among them, cellulose aerogels show great potential as triboelectric materials because of their high porosity, low density, large specific surface area, and strong deformation recovery ability. However, triboelectric nanogenerators based on cellulose aerogels still face serious challenges in transitioning from the laboratory to practical applications. The structure and pore size of cellulose aerogels have not been effectively controlled, and the materials often do not fully meet the performance requirements of nanogenerators because of the limitations in the preparation process. Moreover, existing material modification studies have only partially improved certain indicators. Furthermore, guaranteeing their stability in harsh environments such as high temperature and humidity is difficult.

Future development directions for triboelectric nanogenerators based on cellulose aerogels include ① research and modification of novel cellulose aerogels, ② design and optimization of device structures for specific application scenarios, ③ integration of multifunctional devices based on cellulose aerogels, ④ development of implantable triboelectric nanogenerators and systems based on cellulose aerogels, and ⑤ large-scale preparation processes and equipment for cellulose-based nanogenerators.

2.1.2 Interpretations for three key engineering research fronts

2.1.2.1 Ship digital twin system

Entering the 21st century, the transformation toward digitalization, intelligence, and networking has become an important trend in the global shipbuilding industry. With the maturation of new information technologies such as cloud computing, IoT, big data, and AI, the shipbuilding industry encounters new opportunities for transformative development. Targeting the goals of transformation and upgrading, countries have implemented policies to promote the development of intelligent ships. As an effective means to promote the physical-virtual integration of the shipbuilding industry and facilitate the realization of intelligent ships, the ship digital twin system has received increasing attention, research, and application in the past five years. The essence of the ship digital twin system lies in building a digital virtual ship that is fully mapped and accurately synchronized with the physical ship, thereby breaking through the time and space limitations of the physical world and enabling better analysis, optimization, and enhancement of the physical ship.

Since its proposal, the ship digital twin system has progressed through theoretical framework research, partial application exploration, and in-depth technical studies. It has gradually entered the stage of systematic capability building. Theoretical achievements such as full lifecycle management theory, operational mechanisms, key technologies, and application frameworks have emerged from the theoretical framework research. Guided by these theories, digital twin applications have been explored in key systems such as hull structures, pressure-bearing structures, propulsion systems, and thermal systems, primarily focusing on specific stages within the design, construction, or operation and maintenance processes. As application exploration deepens, specific technical requirements, such as multi-source data sensing and fusion for complex structures,

multidisciplinary coupled model construction and iteration, and reliable ship-shore data transmission and synchronization technologies, have become increasingly prominent, with relevant research gradually progressing. Plans are underway to establish a digital research and development system that encompasses the full lifecycle of ships, incorporating capabilities such as digital twin-based ship design and construction integration, physical-virtual fusion testing, and integrated management and control for models and data.

In the future, the development of ship digital twin systems should concentrate on two main aspects. First, breakthroughs and validations of critical technologies related to sensing, modeling, data, and communication must be achieved in key components and stages, enabling further technological validation at the ship level. Second, research and validation should focus on specific functional technologies of digital twin-driven design, testing, manufacturing, and operations while building an integrated digital research and development system that spans the entire process.

The country with the highest number of core papers published in this front is China, and the countries with the highest citations per paper are Greece, Singapore, and Germany, as shown in Table 2.3. Among the top ten countries with the most published papers, the most collaboration can be observed between China and Poland, as shown in Figure 2.1. The institution with the highest number of core papers published is University of Strathclyde. The institutions with the highest citations per paper are Shanghai Jiao Tong University, Nanyang Technological University, and National Technical University of Athens, as shown in Table 2.4. As shown in Figure 2.2, the most collaboration can be observed between Ocean University of China, Opole University of Technology, and Hebei University of Technology. The top country for citing papers is China, as shown in Table 2.5. The top three institutions for citing papers are Shanghai Jiao Tong University, Harbin Engineering University, and Dalian Maritime University, as shown in Table 2.6. Figure 2.3 shows the roadmap of the engineering research front of “ship digital twin system”.

Table 2.3 Countries with the greatest output of core papers on “ship digital twin system”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	7	30.43	214	30.57	2020.4
2	Germany	4	17.39	159	39.75	2019.2
3	Poland	4	17.39	88	22.00	2021.8
4	Republic of Korea	4	17.39	75	18.75	2021.0
5	UK	4	17.39	61	15.25	2021.8
6	Greece	2	8.70	96	48.00	2019.0
7	Singapore	2	8.70	96	48.00	2019.0
8	Japan	2	8.70	64	32.00	2020.0
9	Denmark	2	8.70	25	12.50	2021.5
10	Netherlands	1	4.35	16	16.00	2022.0

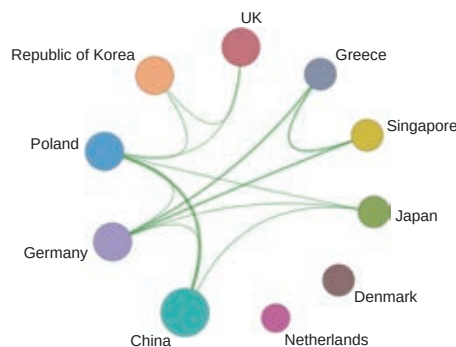


Figure 2.1 Collaboration network among major countries in the engineering research front of “ship digital twin system”

Table 2.4 Institutions with the greatest output of core papers on “ship digital twin system”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Strathclyde	4	17.39	61	15.25	2021.8
2	Ocean University of China	3	13.04	89	29.67	2021.3
3	Nanyang Technological University	2	8.70	96	48.00	2019.0
4	National Technical University of Athens	2	8.70	96	48.00	2019.0
5	University of Duisburg-Essen	2	8.70	91	45.50	2018.0
6	Hebei University of Technology	2	8.70	69	34.50	2021.5
7	Opole University of Technology	2	8.70	69	34.50	2021.5
8	Seoul National University	2	8.70	36	18.00	2021.0
9	Technical University of Denmark	2	8.70	25	12.50	2021.5
10	Shanghai Jiao Tong University	1	4.35	60	60.00	2018.0

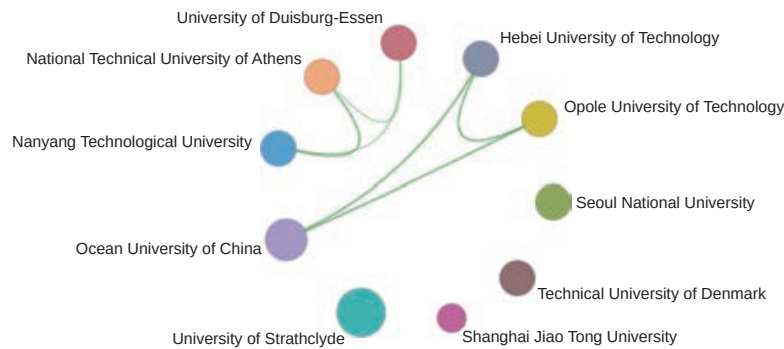


Figure 2.2 Collaboration network among major institutions in the engineering research front of “ship digital twin system”

Table 2.5 Countries with the greatest output of citing papers on “ship digital twin system”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	208	50.61	2021.8
2	Republic of Korea	38	9.25	2022.0
3	Japan	26	6.33	2021.5
4	UK	25	6.08	2022.0
5	Norway	22	5.35	2021.8
6	Germany	18	4.38	2020.0
7	Poland	18	4.38	2022.5
8	Singapore	16	3.89	2021.3
9	USA	16	3.89	2021.6
10	India	13	3.16	2021.7

Table 2.6 Institutions with the greatest output of citing papers on “ship digital twin system”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Shanghai Jiao Tong University	38	20.11	2021.3
2	Harbin Engineering University	27	14.29	2021.1
3	Dalian Maritime University	21	11.11	2021.9
4	University of Strathclyde	18	9.52	2021.9
5	Seoul National University	16	8.47	2021.9
6	Nanyang Technological University	13	6.88	2020.9
7	Wuhan University of Technology	12	6.35	2021.8
8	Ocean University of China	12	6.35	2022.6
9	National University of Defense Technology	11	5.82	2022.1
10	Hiroshima University	11	5.82	2021.4

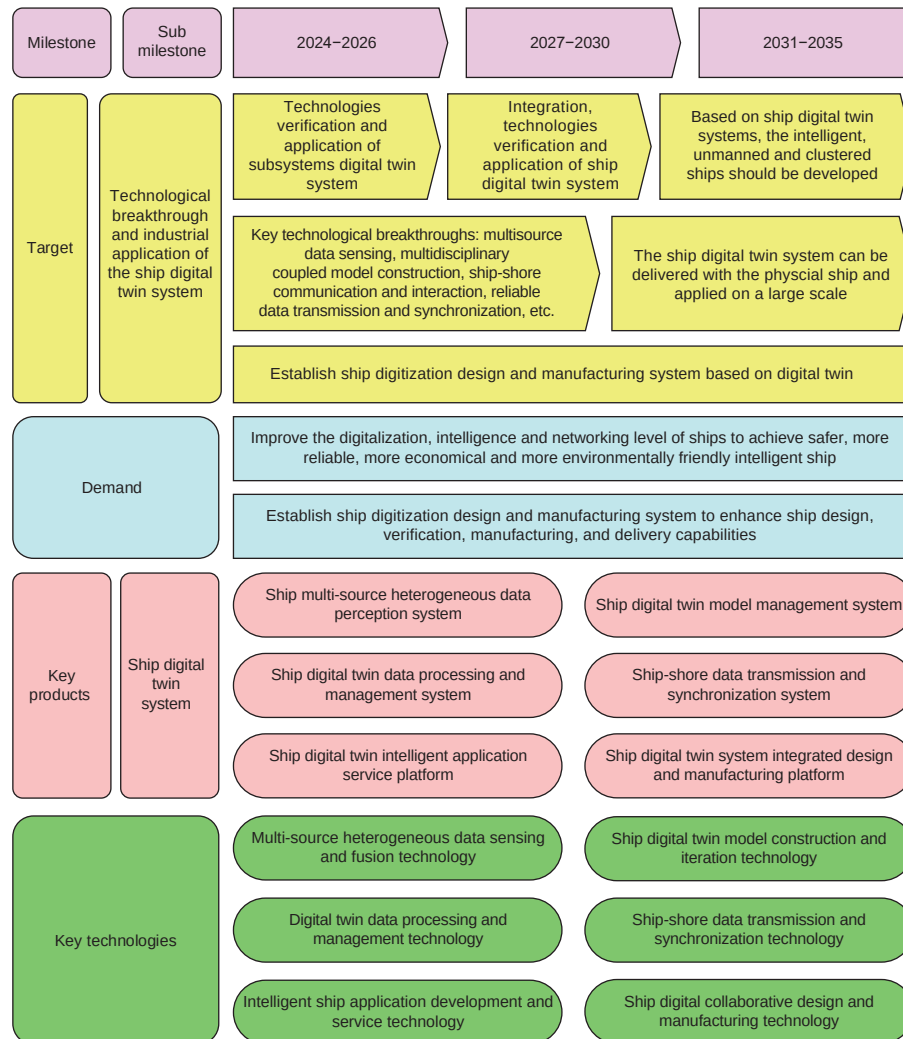


Figure 2.3 Roadmap of the engineering research front of “ship digital twin system”

2.1.2.2 Offshore floating solar power generation

With the carbon peaking and carbon neutrality goals, China is developing a new power system led by new energy and promoting related industries. The widespread availability of solar energy and the flexible application of PV power generation have spurred rapid development in China's PV industry. Currently, PV projects in China are mainly concentrated on land, which requires sizable land areas. Coastal regions face land scarcity, making offshore floating PV an ideal solution as it does not occupy land, offers substantial capacity, and can integrate with offshore wind power, energy storage, and marine aquaculture. These advantages address land-based power generation challenges and have made offshore floating PV a development trend in China's coastal regions.

To survive in the harsh and volatile marine environment, the structural design, hydrodynamic response, and structural response of offshore floating PV power systems, as well as the performance of PV components, have become current research hotspots in the field of offshore floating PV.

China's research and development in the field of offshore floating PV power generation has been progressing rapidly. The relevant research can be mainly divided into four aspects:

- 1) Structural design optimization of offshore floating solar power systems. Referring to the inland water floating PV systems, researchers have proposed various structural forms, such as semi-submersible platform types, multi-module floating types, and flexible membrane type floating PV power generation devices. The development trends in this direction include the optimized design of multi-module floating array structures and materials, as well as the design of new connectors.
- 2) Environmental impact assessment of offshore floating solar power systems. Researchers have evaluated the system's impact on marine life, water quality, and ocean currents, and have formulated corresponding environmental protection measures. Developing a comprehensive environmental evaluation system, promoting the harmonious coexistence of offshore floating PV and the marine environment, and coordinating the development with marine fisheries, seawater desalination, offshore wind power, and other marine industries to achieve resource recycling are the development trends in this direction.
- 3) Efficiency improvement of offshore floating solar power systems. Researchers have conducted experimental testing, evaluation, and optimization of the survivability and power generation efficiency of PV components in the marine environment. The development trend in this direction is to further improve the power generation efficiency of PV components at sea through technologies such as water cooling and sun tracking.
- 4) Integration technologies. How to efficiently integrate key components such as PV modules, power conversion, and collection circuits is a major challenge. Optimizing the coordination of subsystems and integrating with other offshore new energy devices is the development trend in this direction.

In summary, the technology of offshore floating PV power generation has important research value in multiple disciplines such as marine engineering, environmental science, electrical engineering, and system engineering. Achieving the carbon peaking and carbon neutrality goals, strengthening the marine economy, and building an ecological civilization are critical for China. Future technological breakthroughs and industrial applications in this field will provide new momentum for building a maritime power.

The top countries with the highest number of core papers published in this front is Norway, and the countries with the highest citations per paper are Italy, China, and Sweden, as shown in Table 2.7. It can be observed that Spain collaborates with Norway, China collaborates with Sweden, while Germany collaborates with both Italy and Canada, as shown in Figure 2.4. Institutions with the highest number of core paper are Equinor Public Co., Ltd. and European Commission. Institutions with the highest number of highest citations per paper are University of Catania and Koine Multimedia Limited Liability Company, as shown in Table 2.8. It can be observed that there is collaboration between Koine Multimedia Limited Liability Company and University of Catania, between Amirkabir University of Technology and University of Tehran, and between Mälardalen University and Shandong University, as shown in Figure 2.5. The top country for citing papers is China, as shown in Table 2.9. The top three institutions for citing papers are North China Electric Power University, Shandong University, and University of Catania, as shown in Table 2.10. Figure 2.6 shows the roadmap of the engineering research front of "offshore floating solar power generation".

Table 2.7 Countries with the greatest output of core papers on “offshore floating solar power generation”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Norway	4	25.00	164	41.00	2020.8
2	Italy	3	18.75	229	76.33	2020.3
3	Iran	2	12.50	110	55.00	2020.0
4	Germany	2	12.50	71	35.50	2021.0
5	Spain	2	12.50	36	18.00	2022.5
6	China	1	6.25	67	67.00	2019.0
7	Sweden	1	6.25	67	67.00	2019.0
8	Brazil	1	6.25	64	64.00	2018.0
9	USA	1	6.25	64	64.00	2020.0
10	Canada	1	6.25	57	57.00	2020.0

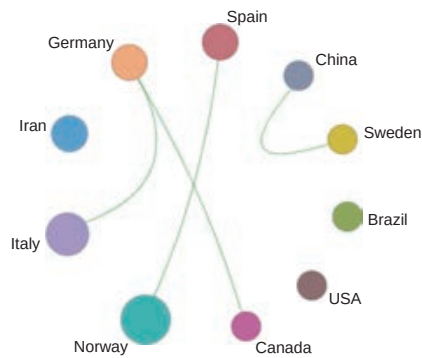


Figure 2.4 Collaboration network among major countries in the engineering research front of “offshore floating solar power generation”

Table 2.8 Institutions with the greatest output of core papers on “offshore floating solar power generation”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Equinor Public Co., Ltd.	2	12.50	114	57.00	2020.0
2	European Commission	2	12.50	83	41.50	2021.5
3	University of Catania	1	6.25	146	146.00	2018.0
4	Koine Multimedia Limited Liability Company	1	6.25	146	146.00	2018.0
5	Amirkabir University of Technology	1	6.25	81	81.00	2019.0
6	University of Tehran	1	6.25	81	81.00	2019.0
7	Mälardalen University	1	6.25	67	67.00	2019.0
8	Shandong University	1	6.25	67	67.00	2019.0
9	Federal University of Itajubá	1	6.25	64	64.00	2018.0
10	Colorado School of Mines	1	6.25	64	64.00	2020.0

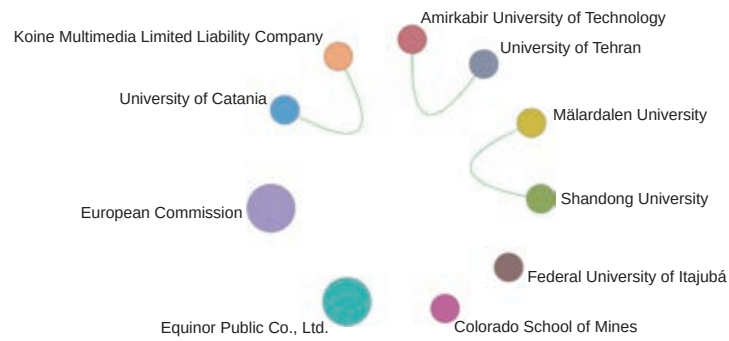


Figure 2.5 Collaboration network among major institutions in the engineering research front of “offshore floating solar power generation”

Table 2.9 Countries with the greatest output of citing papers on “offshore floating solar power generation”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	95	27.14	2021.9
2	India	40	11.43	2021.5
3	Italy	36	10.29	2021.8
4	UK	30	8.57	2021.9
5	USA	28	8.00	2021.2
6	Spain	25	7.14	2022.3
7	Brazil	22	6.29	2021.4
8	Iran	22	6.29	2021.4
9	Republic of Korea	18	5.14	2021.6
10	Singapore	17	4.86	2021.7

Table 2.10 Institutions with the greatest output of citing papers on “offshore floating solar power generation”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	North China Electric Power University	11	11.11	2021.3
2	Shandong University	11	11.11	2021.5
3	University of Catania	11	11.11	2021.5
4	Port Said University	10	10.10	2022.3
5	University of Tehran	9	9.09	2021.1
6	Chinese Academy of Sciences	9	9.09	2021.7
7	National University of Singapore	8	8.08	2021.2
8	Federal University of Rio de Janeiro	8	8.08	2021.1
9	European Commission	8	8.08	2022.1
10	University of Naples Federico II	7	7.07	2021.4

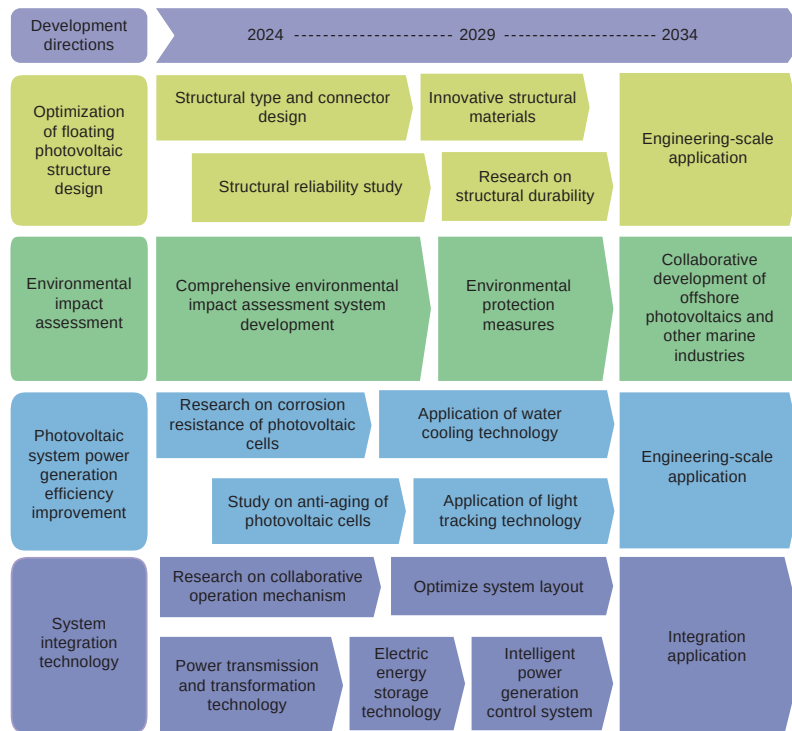


Figure 2.6 Roadmap of the engineering research front of "offshore floating solar power generation"

2.1.2.3 Scene parsing based on depth images

With the success of autonomous driving and robot navigation technologies in the AI 2.0 era, safety hazards in long-tail scenarios have become the biggest obstacle to the large-scale implementation of such technologies. A significant portion of these safety hazards is caused by perception failure or perception bias. Using advanced perception technology to reduce perception bias and perception failure is of considerable importance for improving the accuracy of autonomous driving system decisions and reducing accidents caused by autonomous driving. Among numerous perception technologies, scene parsing technology has become one of the most commonly used perception methods for autonomous driving due to its dense prediction of the entire scene. Stereo cameras have the advantages of low cost and a large amount of information. Therefore, scene parsing technology based on depth images has become one of the scene parsing technologies with the most development potential. Using depth images for scene parsing was first proposed in 2013. With the rapid development of hardware devices such as stereo cameras and graphics processing units, as well as the remarkable performance improvement of AI basic algorithms such as neural networks, the accuracy and stability of scene parsing technology based on depth images have been markedly improved, making it a popular technology in the perception direction.

The scarcity of high-quality data, the diversity of real-world environments, and the limited computing resources can be addressed through the following: improving the utilization of weakly labeled or unlabeled data, improving the capability to balance memory and generalization in the cross-domain process, lightweighting the network structure, and improving the capability to associate temporal information, which have become research hotspots in the field of scene parsing based on depth images. Related research can be divided into three aspects: first, in terms of data, the training data can be notably expanded by using weakly labeled data that is easy to obtain. Pre-segmentation and image processing technologies based on large visual models and saliency detection, respectively, are the development trends in this aspect. Second, in terms of neural network structure, effective feature extraction and context association of RGB-D images can be achieved through neural network structures such as encoder-decoder, twin networks, and long short-term memory networks, and generative adversarial and multibranch network structures are the development trends in this aspect. Third, in terms of multimodal information utilization, a comprehensive understanding of the context of scene images can be

realized by using cross-modal and cross-level complementary information. Depth image correction technology based on depth-color channel correlation and semantic segmentation technology guided by high-level semantic features are the development trends in this aspect. Overall, scene parsing technology based on depth images has important research value in multidisciplinary fields such as depth sensor technology, AI, and spatial perception. Moreover, this technology has practical importance for ensuring the safety of on-road autonomous driving cars and improving the perception capabilities of robot operations.

The country with the highest number of core papers published in this front is China, and the country with the highest citations per paper is the Germany, as shown in Table 2.11. Collaboration exist between China and the Singapore, as shown in Figure 2.7. Institution with the highest number of core papers is Zhejiang University of Science and Technology, and the institutions with the highest citations per paper are Ningbo University and Technical University of Ilmenau, as shown in Table 2.12. The most collaboration can be observed between Zhejiang University of Science and Technology and Zhejiang University, as shown in Figure 2.8. The top country for citing papers is China, as shown in Table 2.13. The top three institutions for citing papers are Zhejiang University of Science and Technology, Zhejiang University, and Ningbo University, as shown in Table 2.14. Figure 2.9 shows the roadmap of the engineering research front of “scene parsing based on depth images”.

Table 2.11 Countries with the greatest output of core papers on “scene parsing based on depth images”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	14	93.33	431	30.79	2022.2
2	Singapore	4	26.67	43	10.75	2023.0
3	Germany	1	6.67	63	63.00	2021.0

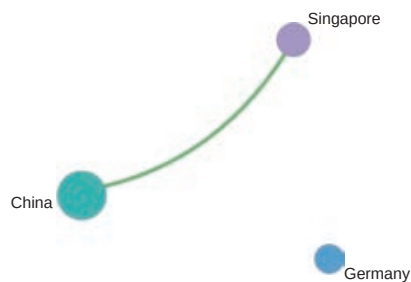


Figure 2.7 Collaboration network among major countries in the engineering research front of “scene parsing based on depth images”

Table 2.12 Institutions with the greatest output of core papers on “scene parsing based on depth images”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Zhejiang University of Science and Technology	12	80.00	375	31.25	2022.4
2	Zhejiang University	9	60.00	285	31.67	2022.4
3	Nanyang Technological University	4	26.67	43	10.75	2023.0
4	Ningbo University	1	6.67	68	68.00	2021.0
5	Technical University of Ilmenau	1	6.67	63	63.00	2021.0
6	The Chinese University of Hong Kong	1	6.67	51	51.00	2020.0
7	Macau University of Science and Technology	1	6.67	51	51.00	2020.0
8	Shenzhen University	1	6.67	51	51.00	2020.0
9	Nanjing University of Science and Technology	1	6.67	10	10.00	2023.0
10	Nankai University	1	6.67	5	5.00	2022.0

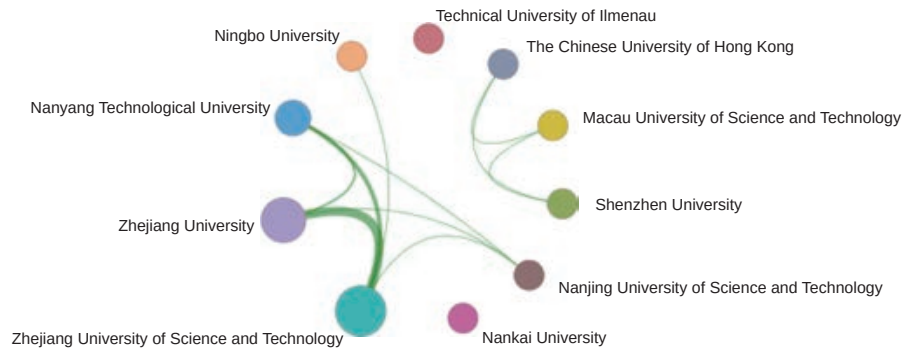


Figure 2.8 Collaboration network among major institutions in the engineering research front of “scene parsing based on depth images”

Table 2.13 Countries with the greatest output of citing papers on “scene parsing based on depth images”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	231	64.53	2022.1
2	USA	28	7.82	2022.0
3	Iran	18	5.03	2021.9
4	Singapore	18	5.03	2022.8
5	Saudi Arabia	11	3.07	2021.9
6	Australia	11	3.07	2021.5
7	Germany	10	2.79	2022.5
8	UK	9	2.51	2022.4
9	Republic of Korea	8	2.23	2022.1
10	Canada	7	1.96	2022.4

Table 2.14 Institutions with the greatest output of citing papers on “scene parsing based on depth images”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Zhejiang University of Science and Technology	75	30.61	2022.0
2	Zhejiang University	67	27.35	2021.9
3	Ningbo University	22	8.98	2021.7
4	Chinese Academy of Sciences	16	6.53	2022.2
5	Nanyang Technological University	16	6.53	2023.0
6	Tsinghua University	9	3.67	2022.7
7	Northeastern University	8	3.27	2022.8
8	Shanghai Jiao Tong University	8	3.27	2021.0
9	University of Washington	8	3.27	2021.8
10	Wenzhou University	8	3.27	2021.5

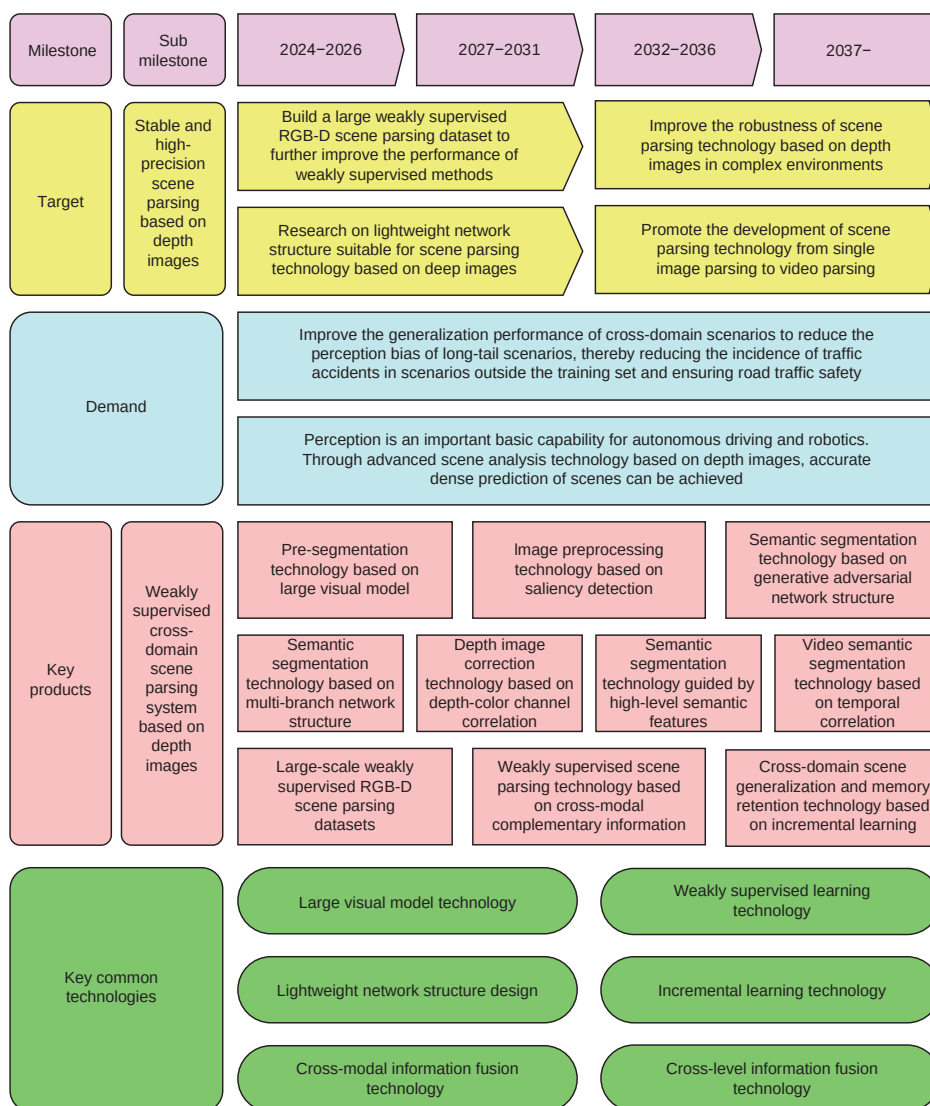


Figure 2.9 Roadmap of the engineering research front of “scene parsing based on depth images”

2.2 Engineering development fronts

2.2.1 Trends in the Top 10 engineering development fronts

Top ten development (as opposed to research) fronts in mechanical and vehicle engineering are listed in Table 2.15. Some of these fronts are characterized by in-depth traditional research: “deep underwater communication and positioning technology”, “comprehensive detection technology for low-altitude unmanned aerial vehicle”, “technology for perception and cooperative control of unmanned surface vessel swarms”, “intelligent embodied AI robotic system”, and “hydrogen fuel aeroengine”. There are also other fronts that are newly emerging: “integrated control technology for the air-sea collaborative heterogeneous unmanned systems”, “high-precision distance recognition technology based on image features”, “continuous ceramic fiber-reinforced metal matrix composites”, “modular advanced armed robot system”, and “prediction of wavy trajectory of hypersonic glide warheads in near space”. Table 2.16 shows the annual publication rate of core patents and related papers from 2018 to 2023. “Integrated control

technology for the air-sea collaborative heterogeneous unmanned systems”, “comprehensive detection technology for low-altitude unmanned aerial vehicle”, and “high-precision distance recognition technology based on image features” are the most significant directions of patent disclosure in recent years.

Table 2.15 Top 10 engineering development fronts in mechanical and vehicle engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Deep underwater communication and positioning technology	184	410	2.23	2021.3
2	Integrated control technology for the air-sea collaborative heterogeneous unmanned systems	728	4 709	6.47	2021.7
3	Comprehensive detection technology for low-altitude unmanned aerial vehicle	776	3 924	5.06	2021.4
4	Technology for perception and cooperative control of unmanned surface vessel swarms	543	7 603	14.00	2021.4
5	High-precision distance recognition technology based on image features	725	3 258	4.49	2021.6
6	Intelligent embodied AI robotic system	4	0	0.00	2022.8
7	Continuous ceramic fiber-reinforced metal matrix composites	10	118	11.80	2020.7
8	Modular advanced armed robot system	8	17	2.12	2021.1
9	Hydrogen fuel aeroengine	46	372	8.09	2021.5
10	Prediction of wavy trajectory of hypersonic glide warheads in near space	199	1 231	6.19	2020.8

Table 2.16 Annual number of core patents published for the Top 10 engineering development fronts in mechanical and vehicle engineering

NO.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Deep underwater communication and positioning technology	16	16	24	29	42	57
2	Integrated control technology for the air-sea collaborative heterogeneous unmanned systems	35	51	54	115	203	270
3	Comprehensive detection technology for low-altitude unmanned aerial vehicle	57	62	82	145	184	246
4	Technology for perception and cooperative control of unmanned surface vessel swarms	35	49	66	98	111	184
5	High-precision distance recognition technology based on image features	24	42	93	123	202	241
6	Intelligent embodied AI robotic system	0	0	0	0	1	3
7	Continuous ceramic fiber-reinforced metal matrix composites	1	2	0	4	2	1
8	Modular advanced armed robot system	2	0	1	0	2	3
9	Hydrogen fuel aeroengine	5	6	1	3	13	18
10	Prediction of wavy trajectory of hypersonic glide warheads in near space	28	24	25	42	35	45

(1) Deep underwater communication and positioning technology

Deep underwater communication and positioning (DUCP) technology focuses on ensuring reliable communication and precise positioning for underwater autonomous vehicles, manned submersibles, and other targets operating at depths exceeding 1 000 m and ranges extending beyond 10 km. This domain encompasses deep-sea communication and positioning technologies. Currently, acoustic waves are the only information carriers capable of effective long-distance propagation underwater, making acoustic communication and positioning techniques the dominant methodologies within DUCP. However, challenges such as rapid signal energy attenuation over long distances, complex multi-path channel structures, and signal confidentiality issues hinder acoustic communication. Consequently, key research directions in DUCP include developing complementary multi-source heterogeneous signal integration, high-speed and large-bandwidth communication systems, and high-precision, low-latency positioning technologies.

Major research endeavors in this field focus on multi-source heterogeneous communication and positioning technologies that integrate acoustic, optical, and electromagnetic signals; fusion of quantum communication with AI; combination of acoustic and inertial navigation systems to enhance positioning accuracy; and the development of integrated deep-sea communication and positioning solutions. The future trajectory of DUCP involves leveraging a communication and positioning framework that primarily relies on acoustic technologies, with supplementary support from optical and electromagnetic methods. The framework simultaneously incorporates emerging technologies such as quantum communication and AI.

Specific technological development trends include low-bandwidth underwater acoustic communication based on in-band full duplex systems; anti-multi-path Doppler effect communication utilizing orthogonal time-frequency spatial modulation; intelligent control systems for underwater communication networks powered by deep learning; multi-source heterogeneous signal fusion technologies integrating acoustic, optical, and quantum signals via deep learning; and collaborative positioning systems that combine inertial navigation with long- and short-baseline methodologies.

(2) Integrated control technology for the air-sea collaborative heterogeneous unmanned systems

The integrated control technology for air-sea collaborative heterogeneous unmanned systems involves the seamless integration of various unmanned systems, such as UAVs, USVs, and AUVs, in operational tasks or scenarios. This technology relies on core capabilities like environmental perception, target detection, tracking and identification, cross-domain communication, intelligent decision-making, autonomous control, and cooperative game theory to enable multidimensional information sharing and coordinated control across time, space, and mode among heterogeneous systems. These systems must maintain stable communication links and possess self-disturbance-resistant coordinated control capabilities under environmental loads such as wind, waves, and currents as well as 3D spatial constraints. To effectively address complex and dynamic operational environments, research in this field has focused on key technologies for unmanned systems, such as cross-domain communication between sea and air, multi-source data fusion, and collaborative control of air-sea unmanned systems.

Future developments in integrated control technology will emphasize low-latency cross-domain networking communication to enhance information perception and fusion in complex cross-domain scenarios. Additionally, attention will be given to resilient autonomous decision making to handle the challenges posed by highly variable environments and strong disturbances, especially under multi-domain coupling and heterogeneous dynamics constraints. By integrating the advantages of near-space unmanned platforms, such as broad vision, prolonged endurance, and cost-efficiency, the aim is to build an “integrated land-sea-air-space” collaborative control platform. This platform will enable effective relay of cross-domain heterogeneous information and enhanced real-time remote sensing situational awareness, comprehensively improving the cross-domain collaborative capabilities of air-sea heterogeneous unmanned systems. This technology is expected to play a crucial role in the development of the marine economy, maintenance of maritime rights, and security of maritime operations.

(3) Comprehensive detection technology for low-altitude unmanned aerial vehicle

In recent years, low-altitude unmanned aerial vehicles (UAVs) have brought great convenience to various fields of society

because of their flexibility, maneuverability, and ease of control. However, they also pose a serious threat to public safety and national security. Many countries have begun to develop anti-UAV systems, and how to realize the efficient and accurate detection of low-altitude UAVs is the key to the effectiveness of the system. Given the target characteristics of the current mainstream low-altitude UAVs, the main detection methods such as radar detection, photoelectric detection, radio frequency detection and acoustic detection have been formed. However, detecting UAVs in complex backgrounds, especially identifying them, remains a challenge for radar detection. RF detection struggles with drones that remain radio silent or use unconventional frequency bands. Acoustic detection is severely affected by environmental noise, with a very limited detection distance. Photoelectric detection is susceptible to weather and struggles to distinguish distant flying targets. To meet the need for efficient identification and countermeasures in complex environments, the future development of comprehensive detection technology for low-altitude UAVs should focus on the following areas: ① multi-source heterogeneous sensor fusion detection based on deep learning, ② multi-site networking detection and identification, ③ mobile tracking detection and reconnaissance/strike integration, and ④ large-scale UAV cluster detection, identification, tracking, and confrontation.

(4) Technology for perception and cooperative control of unmanned surface vessel swarms

The technology for perception and cooperative control of unmanned surface vessel (USV) swarms uses sensors and communication networks to collect and analyze environmental data, design control strategies, and develop software and hardware for wide-area, all-weather, and high-intensity missions. This technology is applied in marine facility inspection, maritime emergency search and rescue, and strategic sea route patrol and warning. Despite achievements in theoretical research, key issues remain, such as low-quality and weakly correlated data, incomplete and unclear target recognition, and instability in navigation and control. In complex marine environments, USV swarms aim to achieve wide-area surveillance. However, obtaining relational information about entities is challenging due to sparse and incomplete data. This problem results in weak perception capabilities of single USVs, substantial inconsistencies across multiple USVs, low knowledge graph understanding, and missing semantic information. During mission execution, wave disturbances can cause rolling, pitching, and yawing, affecting the accuracy and safety of trajectory tracking. High-threat targets, strong waves and currents, and widely distributed obstacles can also lead to coordination failures, inter-vessel conflicts, and navigation instability.

Main research topics include integrating multi-source heterogeneous low-quality information, 3D reconstruction and target recognition in complex marine scenarios, and high-precision cooperative control and adversarial gaming. In the future, perception and cooperative control technology will trend toward high levels of swarming intelligence. The cross-domain cooperation of USVs with unmanned aerial vehicles (UAVs) and unmanned underwater vehicles (UUVs) will be required to achieve multi-dimensional situational awareness and operational decision-making, ensuring reliability and safety in complex marine environments and adversarial conditions.

(5) High-precision distance recognition technology based on image features

High-precision ranging technology based on image features utilizes feature information in target images to obtain distance, depth, and position. It is an important branch of computer vision and machine learning, applied in precision machine measurement, high-precision motion positioning, robotic arm control, real-time detection of geological disasters, spacecraft docking, automated operation guidance of robotic arms, and high-precision target positioning in space.

Current technical directions include algorithm optimization to improve the efficiency and accuracy of image feature extraction and matching, multi-sensor fusion to combine image ranging with other sensor data (e.g., radar and ultrasound) for enhanced accuracy and robustness, and image processing to address interference and environmental impacts. This technology has broad application prospects and market potential. Continuous advancements in computer vision, image processing, and deep learning will expand its applications in intelligent transportation, precision manufacturing, and high-precision robotics, greatly improving automation and intelligence in these fields.

(6) Intelligent embodied AI robotic system

Embodied AI robots integrate AI algorithms with physical robotic systems, enabling perception, learning, reasoning, and action in the real world. These robots possess traditional AI cognitive abilities and interact with the physical environment, achieving natural and flexible intelligent behavior. This technology combines cutting-edge research from multiple fields to create robotic systems capable of autonomously adapting to complex environments. Key technical areas include multimodal perception and fusion, motion control and planning, human-robot interaction, deep learning and reinforcement learning, and knowledge representation and reasoning. As the ideal platform for AI applications, embodied AI robotics has become a focal point in international robotics research. Future development will focus on enhancing robots' autonomous learning capabilities, social intelligence, adaptability, and innovation skills. Ethical and safety considerations will be strengthened to ensure robots adhere to social norms and moral standards. The advancement of embodied AI technology is driving robotics development and expanding its applications across various fields. It is reshaping human-machine relationships, bringing innovative opportunities and challenges to industries such as manufacturing, healthcare, and education, potentially leading to the next generation of intelligent revolution.

(7) Continuous ceramic fiber-reinforced metal matrix composites

Continuous ceramic fiber-reinforced metal matrix composites are a class of materials in which continuous ceramic fibers are embedded within a metal matrix. These reinforcements notably enhance the mechanical properties, corrosion resistance, and wear resistance of the metal. Originally developed with continuous carbon fiber-reinforced aluminum matrix composites, this technology has expanded to include fibers such as alumina and silicon carbide, as well as metal matrices like titanium alloys, magnesium alloys, and others. However, the introduction of these new materials poses challenges in fiber-metal interface compatibility and the fabrication processes of continuous fiber preforms.

At present, domestic and foreign research focuses on several areas: ① surface coating of fibers and filament preparation, ② design and optimization of fiber arrangements through multi-scale, multi-physics field simulations, and ③ improvements in metal matrix composite processes, integrating advanced manufacturing technologies.

Future development trends include: design of fiber arrangements and structural topology optimization; modulation of fiber-metal interface properties; additive manufacturing of complex continuous fiber preforms; numerical simulation and process pathway planning for metal matrix composites; low-cost, large-scale composite component manufacturing with shortened processes; performance evolution, control, and evaluation under service conditions; and increasing interest in intelligent component design with "stimulus-response" characteristics, alongside high-precision and high-efficiency multi-material integrated preparation and processing technology.

(8) Modular advanced armed robot system

The advanced armed robot system consists of a motion platform and task payload, designed for special combat tasks. Motion platforms can be configured for ground, air, water, and underwater operations, whereas task payloads include perception, reconnaissance, strike, and guidance. These systems can be controlled remotely or operate autonomously, serving as fundamental equipment in future unmanned combat systems. They offer flexible movement modes and multiple task payload options. They also can perform tasks in harsh and dangerous environments and reduce casualties.

Future combat environments will increase the complexity of motion platforms and task payloads, demanding higher precision and intelligence. Current research focuses on modular drive transmission mechanisms for high-performance motion platforms, task payload based system configuration design, plug-in modular task payload design and precision control, motion environment perception and target recognition, data link transmission delay compensation control, integrated power module design, and efficient human-computer interaction. Technological development trends include optimizing variable configuration drive mechanisms for cross-media motion platforms, intelligent high-precision collaboration and integrated safety control for motion platforms and task payloads, autonomous decision-making, intelligent task planning, and multi-robot high-performance

collaboration.

(9) Hydrogen fuel aeroengine

The hydrogen fuel aeroengine is a type of aeroengine that uses hydrogen as fuel and converts it into mechanical energy through chemical reactions. This aeroengine can be divided into a hydrogen fuel turbine engine and a hydrogen fuel cell engine. The hydrogen fuel aeroengine is designed to propel aircraft while reducing the emissions of greenhouse gases and other pollutants. Hydrogen fuel aeroengines show broad application prospects in the fields of military and civilian aviation equipment due to the advantages of liquid hydrogen fuel, such as zero carbon emissions, low-temperature storage, and ease of preparation. Compared with traditional aeroengines, hydrogen fuel aeroengines not only demonstrate advantages in reducing carbon emissions but also possess good starting performance, low fuel consumption, and high unit power density.

The main technical directions in this field currently include hydrogen fuel storage and transportation technology, efficient combustion technology, advanced material development, intelligent control, and detection technology. These technical directions aim to solve the problems in the fields of hydrogen cycle, hydrogen combustion, hydrogen control, and hydrogen damage. With the global shift to sustainable development, the efficiency, safety, and reliability of hydrogen fuel aeroengines will continue to improve in the future. These improvements will become an important development direction for the aviation industry and promote the achievement of carbon peaking and carbon neutrality goals in China.

(10) Prediction of wavy trajectory of hypersonic glide warheads in near space

The prediction of the wavy trajectory of hypersonic glide warheads in near space (20–100 km in altitude) involves accurately forecasting the motion trajectories of glide warheads through mathematical modeling, simulation analysis, and real-time tracking. These warheads, actuated by aerodynamic and servo control mechanisms, travel along wavy or jumping trajectories in near space, exhibiting strong maneuverability and penetration performance, which complicates interception by traditional methods. The wavy trajectory of glide warheads is currently derived from the trajectory theory proposed by Qian Xuesen, resembling the Sangar trajectory of a skipping stone. As these warheads navigate through near space, their dynamic parameters present uncertainties, and their trajectories comprise both jumping and gliding components.

At present, major research focuses on precise aerodynamic parameters and control models and trajectory prediction methods based on motion law recognition, control pattern identification, and combat intention judgment. Additionally, advancements in high-resolution acoustic and photoelectric sensor technologies and detection techniques are crucial. The integration of multi-source data fusion techniques using AI and fast-processing intelligent algorithms is also a major area of development. Specifically, the technology trend aims at creating precise dynamic models for hypersonic glide warheads in complex flight environments, including accurate evaluation of lift and drag coefficients and dynamic derivatives for control. High-precision sensor technologies are being developed to obtain accurate flight data on the warheads, alongside autonomous detection and recognition technologies, analysis and online data processing methods, and high-precision ballistic trajectory simulations combined with intelligence optimization algorithms. These efforts aim to achieve real-time precise trajectory predictions for hypersonic glide warheads to provide basic theoretical foundations and key techniques for developing anti-missile systems.

2.2.2 Interpretations for three key engineering development fronts

2.2.2.1 Deep underwater communication and positioning technology

As human marine activities such as exploration, investigation, and resource development in the deep sea increase, real-time monitoring of the operational status of underwater vehicles and platforms becomes crucial. High-precision, low-latency deep underwater communication and positioning (DUCP) technology is essential for enhancing the stability of deep-sea working

platforms, ensuring safety, and improving the efficiency of deep-sea exploration and resource development. Terrestrial communication signals, such as electromagnetic and light waves, suffer severe attenuation underwater. In contrast, low-frequency, high-power acoustic waves can propagate thousands of kilometers underwater, making them the best means for long-range underwater wireless communication. However, during long-distance propagation, challenges such as acoustic signal attenuation, complex multi-path channel structures, and omnidirectional propagation can reduce communication rates, decrease positioning accuracy, and compromise confidentiality. Advancements in sensor and AI technologies are driving DUCP technology toward integrating various underwater communication methods, leveraging AI, big data, and other technologies to achieve increased intelligence and autonomy. Efforts are also being exerted to standardize and optimize underwater communication and positioning technologies to improve metrics such as transmission rates, communication distances, bit error rates, and positioning accuracy.

To enhance the stability of deep underwater communication and improve positioning accuracy, several technologies have become prominent in DUCP. Key research areas include multi-source heterogeneous communication and positioning technologies, integration of emerging technologies such as quantum communication and AI, and acoustic-inertial guidance combination positioning technologies. Although research on DUCP in China began relatively late, it has rapidly developed in recent years. Remarkable advancements include optimizing multi-source heterogeneous communication and positioning technologies using advanced modulation techniques (e.g., OFDM and MIMO) and coding techniques, which enhance acoustic communication rates and distances. Long-distance optical communication is achieved through high-power lasers and optical receiving technologies, whereas new frequency bands and modulation techniques for radio communication are being explored. Research also focuses on quantum key distribution and magnetic induction signal propagation characteristics, integrating acoustic methods with optical and radio technologies and leveraging emerging technologies such as quantum computing and AI. Additionally, in-band full-duplex hydroacoustic communication technology aims to increase underwater communication transmission rates and distances while improving positioning accuracy and addressing multipath and Doppler effects. Utilizing the BeiDou navigation system and underwater short-long baseline coordinated positioning technologies facilitates the intelligent regulation and control of underwater communication networks, advancing the intelligence and autonomy of DUCP systems. In conclusion, DUCP technology holds great potential for industrialization and application in deep-sea resource exploration, underwater engineering, marine environment monitoring, national defense, smart ocean development, and emergency rescue. This technology is crucial for ensuring the safety of marine resource exploration and safeguarding national defense at sea.

Currently, the country with the highest number of core patents published in this field is China, and the top country with the highest citations per patent is the USA, as shown in Table 2.17. No collaboration can be observed between these countries with

Table 2.17 Countries with the greatest output of core patents on “deep underwater communication and positioning technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	149	80.98	312	76.10	1.00
2	Japan	14	7.61	10	2.44	2.00
3	USA	8	4.35	68	16.59	3.00
4	Republic of Korea	5	2.72	4	0.98	4.00
5	India	2	1.09	0	0.00	5.00
6	Netherlands	1	0.54	7	1.71	6.00
7	Canada	1	0.54	6	1.46	7.00
8	Saudi Arabia	1	0.54	2	0.49	8.00
9	Italy	1	0.54	1	0.24	9.00
10	Norway	1	0.54	0	0.00	10.00

the greatest output of core patents. The top four institutions with the highest number of core patents are China Shipbuilding Industry Corporation, National Deep Sea Center, Institute of Acoustics of Chinese Academy of Sciences, and Harbin Engineering University, as shown in Table 2.18. Collaboration can be observed between National Deep Sea Center and Changchun University of Science and Technology, as shown in Figure 2.10. Figure 2.11 shows the roadmap of the engineering development front of “deep underwater communication and positioning technology”.

Table 2.18 Institutions with the greatest output of core patents on “deep underwater communication and positioning technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Shipbuilding Industry Corporation	8	4.35	15	3.66	1.88
2	National Deep Sea Center	6	3.26	37	9.02	6.17
3	Institute of Acoustics, Chinese Academy of Sciences	6	3.26	34	8.29	5.67
4	Harbin Engineering University	6	3.26	13	3.17	2.17
5	Zhejiang University	4	2.17	17	4.15	4.25
6	Changchun University of Science and Technology	3	1.63	6	1.46	2.00
7	Japan Agency for Marine-Earth Science and Technology	3	1.63	3	0.73	1.00
8	Tianjin University	3	1.63	3	0.73	1.00
9	Qilu University of Technology (Shandong Academy of Sciences)	3	1.63	2	0.49	0.67
10	Sanya Deep Sea Science and Engineering Research Institute	3	1.63	2	0.49	0.67

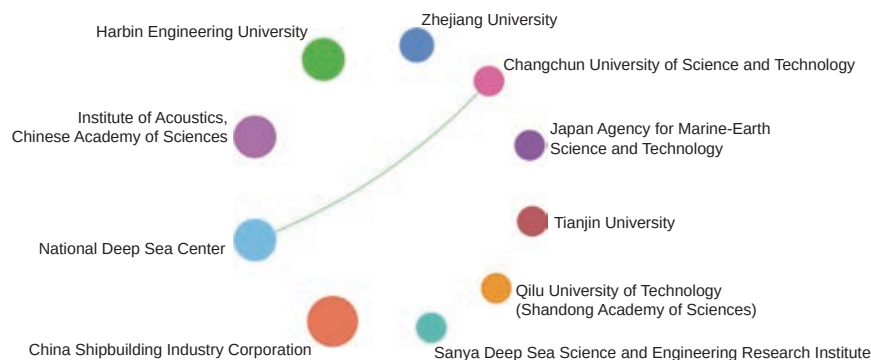


Figure 2.10 Collaboration network among major institutions in the engineering development front of “deep underwater communication and positioning technology”

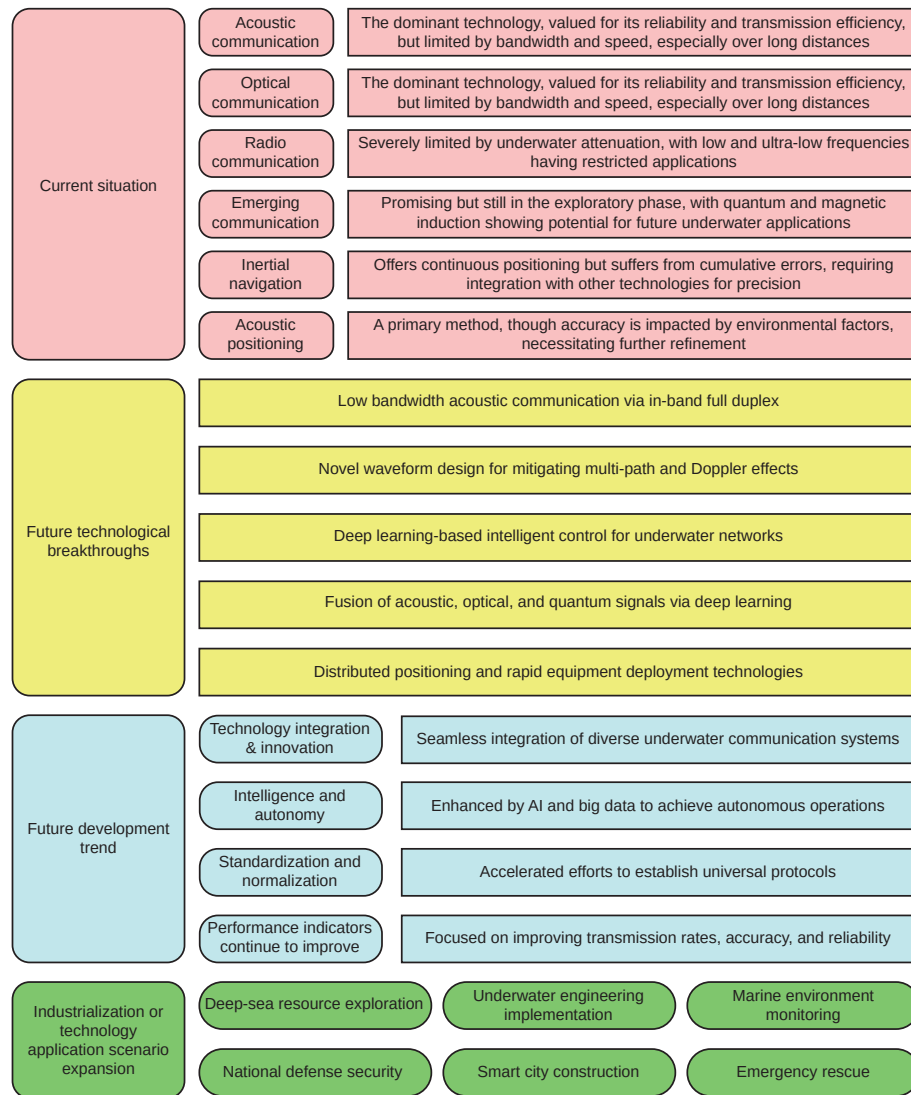


Figure 2.11 Roadmap of the engineering development front of “deep underwater communication and positioning technology”

2.2.2.2 Integrated control technology for the air-sea collaborative heterogeneous unmanned systems

The integrated control technology for air-sea collaborative heterogeneous unmanned systems (USV, UAV, and AUV) is at the forefront of maritime science and military applications, representing a key direction in the development of intelligent unmanned systems. As unmanned systems become increasingly utilized and as computer, communication, and distributed control technologies continue to integrate into marine science, leading maritime nations like the USA are actively advancing cross-domain heterogeneous unmanned equipment, such as UAVs, USVs, and AUVs. These nations are driving the evolution of unmanned systems from single-domain individual platforms to single-domain clusters and further to cross-domain collaborative efficiency enhancements. The integrated control technology for these air-sea collaborative systems is fundamental to creating disruptive capabilities in intelligent unmanned systems. Compared with homogeneous systems operating within a single domain, these heterogeneous systems offer complementary advantages and comprehensive linkages, considerably enhancing unmanned system functionality and expanding their application scope. Strengthening research in this technology and fully utilizing the dynamic complementary advantages across multiple domains is

strategically important for socio-economic development and national security.

The integrated control of air-sea collaborative heterogeneous unmanned systems is a multidisciplinary frontier, encompassing control theory, AI, information theory, communications engineering, and game theory. Research in this field primarily focuses on three aspects:

- 1) Cross-domain multi-node self-organizing network communication-computing integration technology. This area explores high-reliability and low-latency cross-domain networking communication theories, designs cross-layer data interconnection and sharing mechanisms, and establishes communication infrastructures based on AI and edge-cloud collaboration. These efforts support decision-making and control under complex environmental disturbances and spatial constraints.
- 2) Multi-domain coupling and heterogeneous dynamics constraints for resilient decision-making. Research in this area elucidates the coupling effects between the environment, mission objectives, and air-sea heterogeneous platforms. It involves task scheduling and dynamic planning under cross-domain heterogeneous dynamics constraints and establishes a robust and resilient decision-making system to facilitate the autonomous learning and evolution of unmanned decision systems, thereby enhancing collaborative efficiency.
- 3) Integrated collaborative control of air-sea unmanned systems with strong heterogeneous dynamic characteristics. This area combines real-time feedback and adjustment mechanisms to construct an integrated control model that unifies and adapts to the dynamic characteristics of different cross-domain vehicles. It also explores human-machine multimodal interaction control laws to support efficient collaboration between different platforms.

In summary, the continuous development of integrated control technology for air-sea collaborative heterogeneous unmanned systems is of practical importance for ensuring the safety of a country's maritime activities, developing deep-sea resources, and advancing the marine economy.

The country with the highest number of core patents published in this field is China; the top country with the highest citations per patent is Israel, as shown in Table 2.19. No collaboration can be observed between the countries with the greatest output of core patents. The top three institutions with the highest number of core patents are Nanjing University of

Table 2.19 Countries with the greatest output of core patents on “integrated control technology for the air-sea collaborative heterogeneous unmanned systems”

No.	Country	Published patents	Percentage of Published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	675	92.72	3 536	75.09	5.24
2	USA	36	4.95	822	17.46	22.83
3	Republic of Korea	2	0.27	12	0.25	6.00
4	Japan	2	0.27	10	0.21	5.00
5	Russia	2	0.27	1	0.02	0.50
6	India	2	0.27	0	0.00	0.00
7	Israel	1	0.14	64	1.36	64.00
8	Chile	1	0.14	25	0.53	25.00
9	Netherlands	1	0.14	6	0.13	6.00
10	Australia	1	0.14	0	0.00	0.00

Aeronautics and Astronautics, National University of Defense Technology and Beihang University, as shown in Table 2.20. Collaboration can be observed between Northwestern Polytechnical University and Xidian University, as well as between China Electronics Technology Group Corporation and Nanjing University of Aeronautics and Astronautics, as shown in Figure 2.12. Figure 2.13 shows the roadmap of the engineering development front of “integrated control technology for the air-sea collaborative heterogeneous unmanned systems”.

Table 2.20 Institutions with the greatest output of core patents on “integrated control technology for the air-sea collaborative heterogeneous unmanned systems”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nanjing University of Aeronautics and Astronautics	37	5.08	244	5.18	6.59
2	National University of Defense Technology	28	3.85	126	2.68	4.50
3	Beihang University	24	3.30	149	3.16	6.21
4	Northwestern Polytechnical University	20	2.75	86	1.83	4.30
5	China Electronics Technology Group Corporation	16	2.20	44	0.93	2.75
6	Hefei University of Technology	15	2.06	220	4.67	14.67
7	State Grid Corporation of China	15	2.06	87	1.85	5.80
8	Beijing Institute of Technology	15	2.06	56	1.19	3.73
9	Dalian Maritime University	13	1.79	84	1.78	6.46
10	Xidian University	12	1.65	63	1.34	5.25

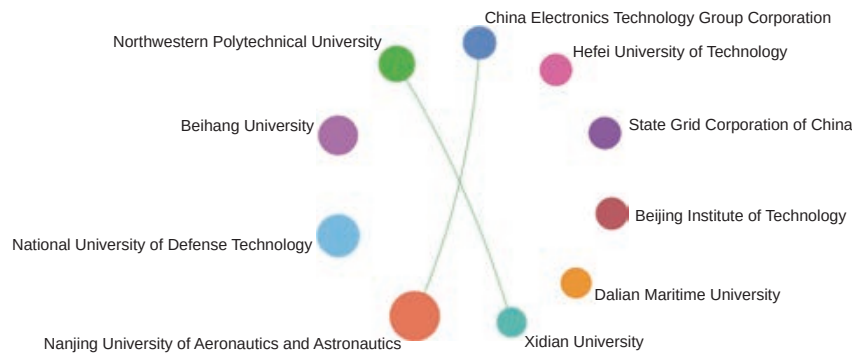


Figure 2.12 Collaboration network among major institutions in the engineering development front of “integrated control technology for the air-sea collaborative heterogeneous unmanned systems”

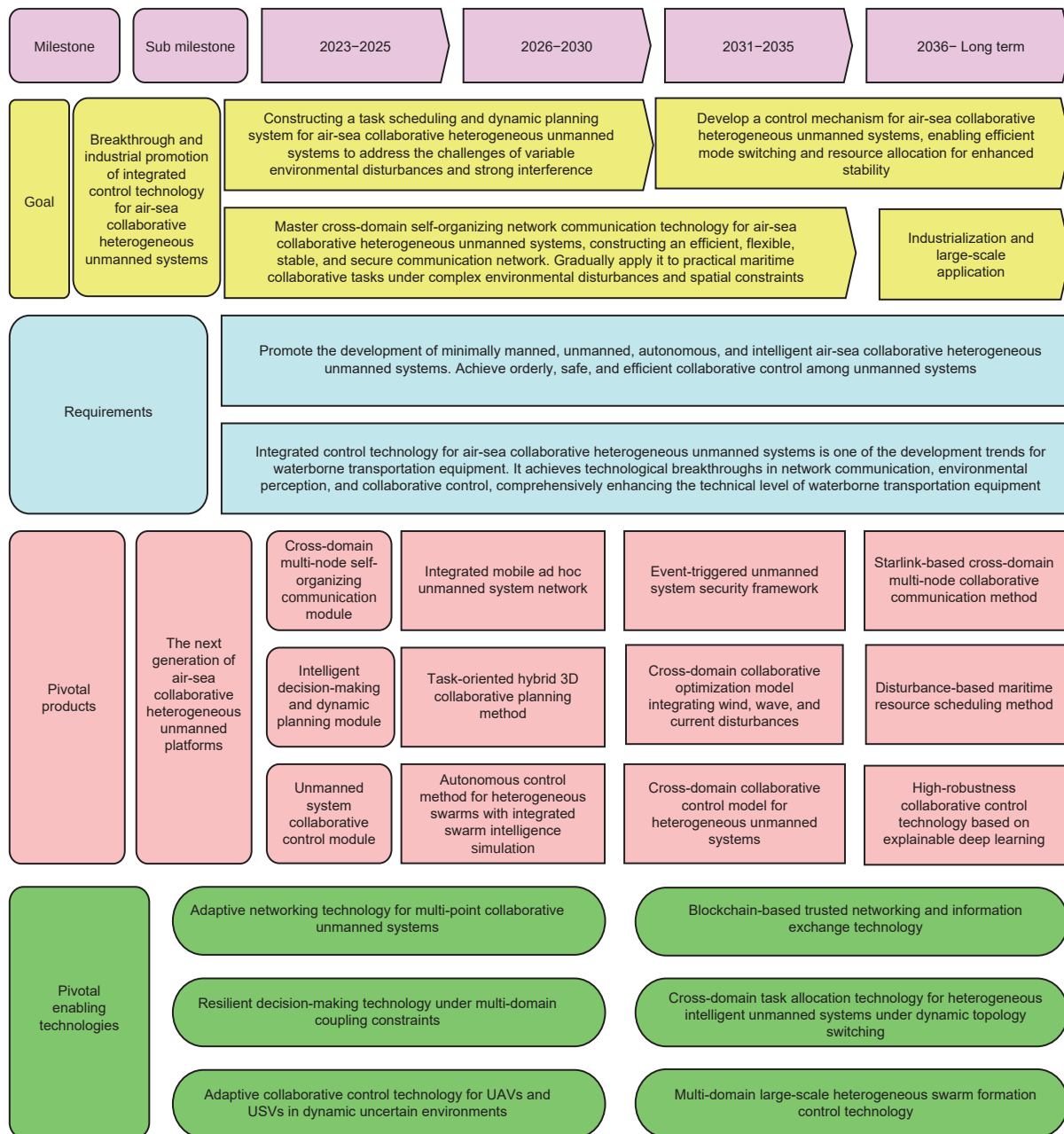


Figure 2.13 Roadmap of the engineering development front of "integrated control technology for the air-sea collaborative heterogeneous unmanned systems"

2.2.2.3 Comprehensive detection technology for low-altitude unmanned aerial vehicle

In recent years, low-altitude UAVs have brought great convenience to various fields of society because of their flexibility, maneuverability, and ease of control. However, they also pose a serious threat to public safety and national security. Many countries have begun to develop anti-UAV systems, and efficient, accurate detection of low-altitude UAVs is key to their effectiveness. Currently, low-altitude UAVs are primarily composed of lightweight non-conductor materials, and the rotation of the motor or rotor during flight generates specific acoustic signals with frequencies in the range of 0.3–20 kHz; they communicate via radio. Given these target characteristics, detection methods such as radar detection, photoelectric detection, radio frequency

detection, and acoustic detection have been developed. However, these methods have various problems, and comprehensive detection technology for low-altitude UAVs has gradually attracted much attention.

At present, some progress has been made in clutter suppression and micro-Doppler signal feature extraction, but detecting UAVs in complex backgrounds, especially UAV recognition, remains a challenge for radar detection. RF detection is effective for identifying drones, but it struggles to detect drones that remain radio silent or use unconventional frequency bands. Although the audio data of drones in various environments has expanded rapidly in recent years, acoustic detection is still unsatisfactory in complex environments like urban areas and has a very limited detection range. Photoelectric detection is susceptible to weather conditions and struggles to distinguish distant flying targets. Although HD/Ultra HD cameras have extended the detection range, they also increase the computational load.

To meet the needs for efficient identification and countermeasures in complex environments, the development direction of comprehensive detection technology for low-altitude UAVs is clear.

- 1) Multi-source heterogeneous sensor fusion detection. Radar and radio frequency detection technology for long-range detection is combined with photoelectric and acoustic detection technology for close-range detection, and complex features are extracted from multi-source heterogeneous data using deep learning.
- 2) Multi-site networking detection. The information obtained by each node detector is fused through the network to enable collaborative detection and comprehensive identification. This approach addresses the issues of insufficient information obtained by a single node, blind spots, and low fault tolerance rates.
- 3) Mobile and tracking detection: The combination of airborne and vehicle-mounted detectors can approach the target to obtain high-quality target information, laying the data foundation for executing complex tasks and facilitating the integration of detection and attack devices.
- 4) Large-scale UAV cluster detection and tracking. Current research primarily focuses on countering a small number of UAVs, but the application of large-scale UAV clusters is becoming an inevitable trend. Realizing the detection, identification, tracking, and confrontation of large-scale UAV clusters is the key direction for future breakthroughs.

The country with the highest number of core patents published in this field is China, and the top country with the highest citations per patent is the USA, as shown in Table 2.21. No collaboration can be observed between the countries with the greatest output of

Table 2.21 Countries with the greatest output of core patents on “comprehensive detection technology for low-altitude unmanned aerial vehicle”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	737	94.97	3 052	77.78	4.14
2	Republic of Korea	15	1.93	109	2.78	7.27
3	USA	13	1.68	752	19.16	57.85
4	Japan	3	0.39	5	0.13	1.67
5	Russia	2	0.26	0	0.00	0.00
6	Sweden	1	0.13	3	0.08	3.00
7	Turkey	1	0.13	3	0.08	3.00
8	Bulgaria	1	0.13	0	0.00	0.00
9	Canada	1	0.13	0	0.00	0.00
10	India	1	0.13	0	0.00	0.00

core patents. The top institutions with the highest citations per patent are Beihang University, Nanjing University of Aeronautics and Astronautics and China Electronics Technology Group Corporation, as shown in Table 2.22. Collaboration can be observed between State Grid Corporation of China and Wuhan University, as well as between AVIC Shenyang Aircraft Design & Research Institute and Beihang University, as shown in Figure 2.14. Figure 2.15 shows the roadmap of the engineering development front of “comprehensive detection technology for low-altitude unmanned aerial vehicle”.

Table 2.22 Institutions with the greatest output of core patents on “comprehensive detection technology for low-altitude unmanned aerial vehicle”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Beihang University	22	2.84	157	4.00	7.14
2	Nanjing University of Aeronautics and Astronautics	20	2.58	38	0.97	1.90
3	China Electronics Technology Group Corporation	18	2.32	43	1.10	2.39
4	State Grid Corporation of China	14	1.80	24	0.61	1.71
5	South China Agricultural University	11	1.42	62	1.58	5.64
6	Northwestern Polytechnical University	11	1.42	54	1.38	4.91
7	AVIC Shenyang Aircraft Design & Research Institute	9	1.16	102	2.60	11.33
8	Wuhan University	9	1.16	19	0.48	2.11
9	Zhejiang University	8	1.03	55	1.40	6.88
10	Harbin Institute of Technology	7	0.90	106	2.70	15.14

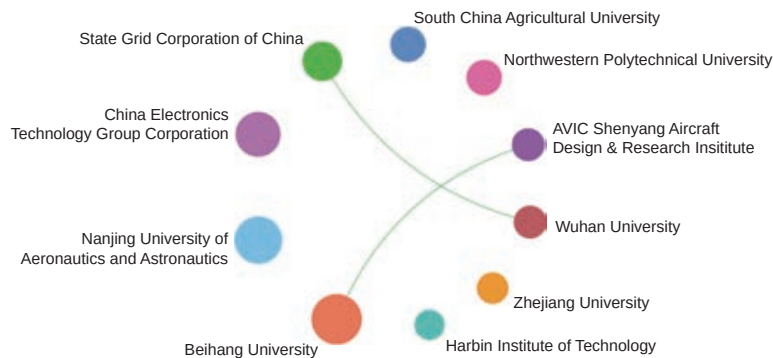


Figure 2.14 Collaboration network among major institutions in the engineering development front of “comprehensive detection technology for low-altitude unmanned aerial vehicle”

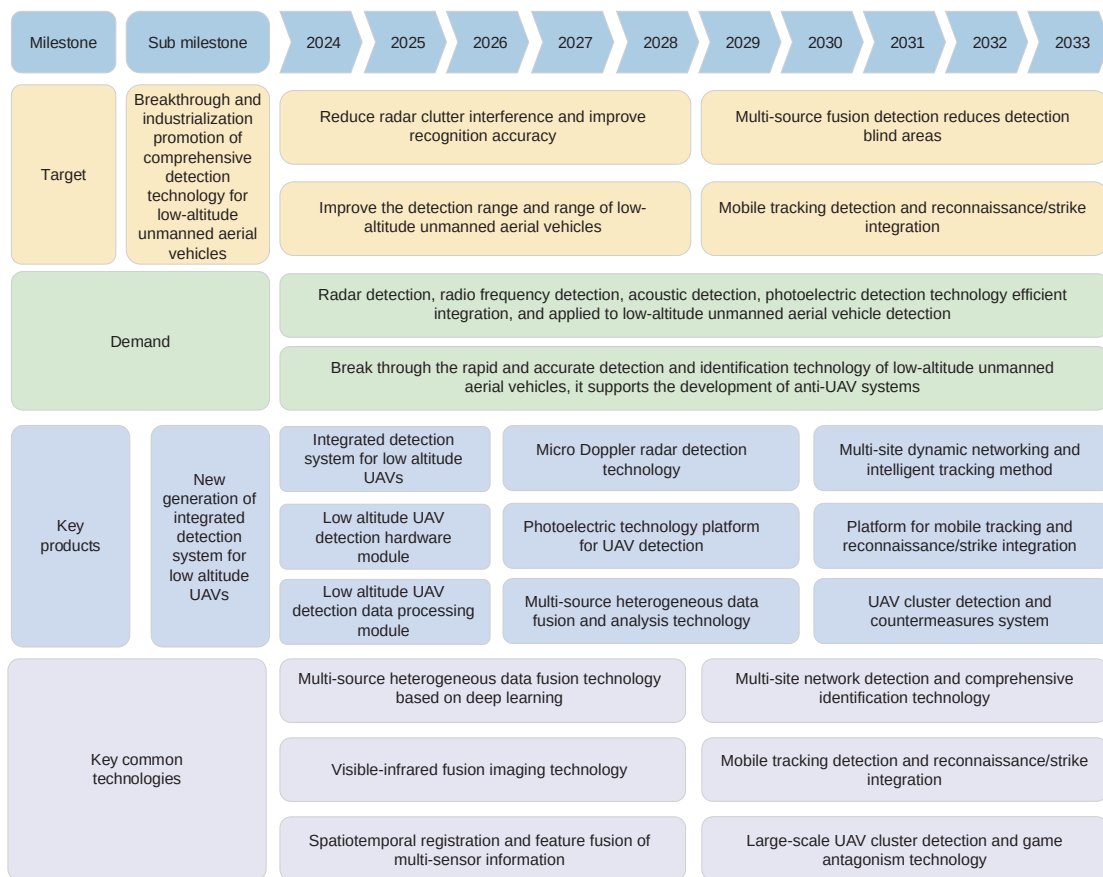


Figure 2.15 Roadmap of the engineering development front of "comprehensive detection technology for low-altitude unmanned aerial vehicle"

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Chapter 3 Information and Electronic Engineering Fronts



3.1 Engineering research fronts

3.1.1 Trends in the Top 10 engineering research fronts

Table 3.1 summarizes the Top 10 engineering research fronts in the field of information and electronic engineering, which encompasses the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. Among them, “low-altitude information network system and integrated sensing and communication technology” is a data mining front, while the rest are fronts nominated by experts. Table 3.2 shows the number of core papers published from 2018 to 2023 related to each research front.

(1) Basic theory and methodology of embodied intelligence

Embodied intelligence refers to the theoretical methods enabling a smart loop of interaction between physical form and the external environment. This paradigm emphasizes that cognition is influenced by the synergy between an intelligent agent’s perception and action, fundamentally integrating morphology, behavior, perception, and learning to enhance overall performance. The foundational theories and methods of embodied intelligence encompass embodied sensing, embodied interaction and collaboration, large embodied models, and behavioral learning.

In contrast to current paradigms in artificial intelligence (AI) research, embodied intelligence places significant emphasis on “proactivity”—leveraging the characteristics of physical form to achieve active control, active sensing, and active learning. This approach not only markedly reduces the complexity associated with data acquisition, data labeling, and model training but also provides valuable insights into energy efficiency and green computing. Key research directions include intelligent robotics, autonomous driving, human-machine interaction, and large embodied models.

Table 3.1 Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Basic theory and methodology of embodied intelligence	270	22 309	82.63	2019.9
2	Theory and design of wafer-scale system-on-chip	141*	4 547	32.25	2021.4
3	Low-altitude information network system and integrated sensing and communication technology	63	5 377	85.35	2021.7
4	Theory of multimodal perceptual and cognitive intelligence	117	11 893	101.65	2020.4
5	Ultra-high sensitivity cross-scale defect detection technology	88	5 027	57.12	2020.1
6	Intelligent scientific computing driven by data and physical laws	62	12 916	208.32	2021.4
7	Distributed planning and intelligent cooperative control for large-scale satellite clusters	61*	504	8.26	2021.6
8	Ultra-large-scale integrated optical computing chips	20	1 793	89.65	2020.5
9	Theory and method of all-optical deep computational imaging	44	6 219	141.34	2020.2
10	Semantic communication theory and technology based on artificial intelligence	29	3 283	113.21	2021.9

* Total number of papers.

Table 3.2 Annual number of core papers published for the Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Basic theory and methodology of embodied intelligence	62	57	57	49	27	18
2	Theory and design of wafer-scale system-on-chip	10	8	17	29	41	36
3	Low-altitude information network system and integrated sensing and communication technology	3	2	1	17	23	17
4	Theory of multimodal perceptual and cognitive intelligence	17	21	22	22	23	12
5	Ultra-high sensitivity cross-scale defect detection technology	16	19	17	17	14	5
6	Intelligent scientific computing driven by data and physical laws	1	2	9	21	17	12
7	Distributed planning and intelligent cooperative control for large-scale satellite clusters	6	4	3	7	14	27
8	Ultra-large-scale integrated optical computing chips	2	4	5	1	6	2
9	Theory and method of all-optical deep computational imaging	5	9	12	8	8	2
10	Semantic communication theory and technology based on artificial intelligence	1	1	1	5	10	11

Embodied intelligence has emerged as a critical driver for advancements in AI and robotics. Looking ahead, as this field promotes research into multimodal fusion perception, self-supervised autonomous learning, and long-term continuous learning, it will facilitate the development of world models that better conform to physical laws. Consequently, embodied intelligence will delve deeper into biomimetic intelligence and human-like intelligence.

(2) Theory and design of wafer-scale system-on-chip

Theory and design of wafer-scale system-on-chip (SoC) refers to the foundational theories of complex system design that integrate domain-specific software and hardware, along with design methodologies for high-density wafer-level integration. It also encompasses efficient mapping and deployment strategies for applications onto wafer-scale chips based on these theories. Wafer-level SoCs embody a physical manifestation of information systems tailored for specific domains through innovations in wafer-level high-density integration processes and co-designed hardware-software architectures. Characterized by ultra-high integration density and highly flexible function deployment, these chips typically exhibit exceptional functional density.

Wafer-level SoCs transcend traditional microelectronics' reliance on advanced process technologies. They achieve the continuation of Moore's Law at the system level via heterogeneous and hetero-material integration, multi-reticle stitching, and wafer-level bonding techniques. Furthermore, they empower the entire process of IC design and application through software-defined architecture, enabling vertical integration across multiple application scenarios and self-evolution with accumulated data.

The research into wafer-level SoC theory and design is rapidly evolving and permeating large-scale information infrastructure like cloud computing, supercomputing, and intelligent computing. This field provides a theoretical foundation for enhancing the performance, efficiency, and processing capabilities of information systems. Key research directions include domain-specific hardware-software co-design architectures and wafer-level integration processes. Domain-specific hardware-software co-design architecture targets common characteristics of domain applications, integrating software and hardware architectures throughout the design and operation of computing systems using unified descriptions and tools. This approach aims to optimize the system across the software-hardware boundary, ensuring efficient collaboration and interaction between software and hardware for superior system performance and efficiency.

Wafer-level integration processes are grounded in advanced integration technology and microelectronics theory, investigating process technologies such as wafer-level bonding and cross-scale high-precision integration, and designing the hardware systems for wafer-level SoCs.

Looking forward, the development of wafer-level SoC theory and design must address four critical areas: reliability design and testing, application deployment optimization, generative on-chip interconnection networks, and generalized robustness technologies for systems. First, more reliable design and testing techniques are required to ensure the production yield and operational reliability of the hardware system. Second, application deployment optimization needs further advancement to achieve efficient mapping of complex applications onto the hardware system. Third, generative structures for on-chip interconnect networks can provide a foundation for future intelligent computing systems. Lastly, generalized robustness technologies for wafer-level SoCs can offer security support for new forms of information infrastructure.

(3) Low-altitude information network system and integrated sensing and communication technology

Low-altitude information network system and integrated sensing and communication (ISAC) technology leverages ground-based communication systems, satellite positioning and navigation systems to establish a dynamic, flexible, and efficient wireless communication and information service network. This network provides comprehensive services such as communication, positioning, navigation, and regulation for low-altitude drones, manned aircraft, and other aerial vehicles, serving as crucial infrastructure to empower applications in the low-altitude economy. Based on large-scale antenna arrays at ground stations, ISAC combines communication and radar sensing functionalities, offering high-data-rate, low-latency communication services alongside real-time sensing, detection, and positioning of passive objects. By leveraging the extensively deployed mobile communication networks, ISAC can provide ubiquitous high-performance communication and sensing services.

The low-altitude information network system and ISAC technology can be categorized into two main types, which encompass communication-assisted sensing and sensing-assisted communication. Communication-assisted sensing aims to use the signals, propagation delays and directions, and network resources provided by communication systems, to support the execution of sensing tasks. By using waveform design, signal transmission, and information sharing schemes, communication-assisted sensing achieves low-cost and high-efficiency ubiquitous sensing. This category can be further subdivided into single-station ISAC and multi-station cooperative ISAC. Sensing-assisted communication, on the other hand, aims to provide feedback on environmental information obtained through sensing to the communication system, such as velocity, delay, and angle, which assists the communication network in dynamically adjusting, optimizing communication resource allocation and scheduling, and interference management, thereby enhancing communication performance.

The future development trends of low-altitude information network systems and ISAC technology include aspects such as air interface and waveform design, architecture and networking, cooperation and integration. First, by designing of integrated communication-sensing waveforms, a unified wireless air interface can be achieved, effectively improving spectral efficiency, and maximizing resource utilization. Second, a natively integrated architecture will facilitate on-demand activation of communication and sensing functions, which supports continuous seamless low-altitude information services through global networking. Finally, deep cooperation across multiple frequency bands, multiple nodes, and multiple modalities will integrate multi-dimensional data. By jointly processing and optimizing multi-source data, the system performance will be further enhanced.

(4) Theory of multimodal perceptual and cognitive intelligence

Theory of multimodal perception and cognitive intelligence primarily refers to the integration of information from multiple sensory channels (such as visual, auditory, tactile, and textual) to achieve comprehensive understanding and analysis of environments or objects. This computational paradigm emulates human multidimensional perception and cognition mechanisms, aiming to enable machines to attain collaborative understanding and reasoning across multimodal data including vision, audition, touch, and more.

Multimodal perception intelligence mainly relies on deep learning, data fusion, and pattern recognition technologies to process and analyze data from different modalities. Research in this area focuses on multimodal data representation, cross-modal information fusion, mining correlations between modalities, and joint optimization of multimodal tasks to improve the accuracy and robustness of perception systems. Multimodal cognitive intelligence centers on the core processes of collaborative handling and fusion of multimodal data, addressing key issues such as cross-modal representation learning, cross-modal generation, and multimodal collaboration. For instance, in the domain of autonomous driving, integrating data from cameras, radar, and LiDAR can

lead to more precise identification and prediction of dynamic objects in the surrounding environment.

Research trends in multimodal perception intelligence include developing more powerful large-scale multimodal pre-trained models to cover a broader range of application scenarios; enhancing real-time data processing capabilities to meet the demands for immediate response in complex environments; and focusing on data synchronization and heterogeneous fusion to boost overall system perceptual ability and adaptability. Multimodal cognitive intelligence is progressively evolving towards a deeper integration of deep neural networks with cognitive science, striving to bridge the semantic gap between modalities and achieve intelligent systems that are closer to human-level cognition. This evolution provides crucial theoretical foundations and technological support for tasks like natural language understanding, visual question answering, and cross-modal retrieval.

(5) Ultra-high sensitivity cross-scale defect detection technology

The rapid advancement of AI has spurred a continuous strong demand for advanced semiconductor chips globally, driving manufacturing process nodes into the 20 Å (2 nm) era and intensifying the competitive landscape. Accompanying smaller critical dimensions in manufacturing are extremely minute defects such as surface deformations, cracks, flaws, and crystal dislocations, presenting greater challenges for semiconductor defect detection, especially at the wafer level. The span of defect sizes can range from 10^7 to 10^8 , leading to issues like missed detections, incorrect inspections, and efficiency concerns becoming increasingly prominent. There is an urgent market need for ultra-high sensitivity, cross-scale defect detection technologies. Not only within chip manufacturing, but also in areas such as large-aperture ultra-precision optical components and large ultra-precision mechanical structures, there is a pressing demand for ultra-sensitive, cross-scale defect inspection.

Key research directions for ultra-high sensitivity, cross-scale defect detection technology include: ① Innovation in high-sensitivity defect detection principles and equipment development. By innovating measurement principles and enhancing instrument design, develop inspection tools with ultra-high resolution and sensitivity to achieve ultra-sensitive and precise detection of defects at even smaller scales. ② Rapid inspection techniques over large measurement ranges. Develop new methods for rapid inspection across large areas, along with high-speed scanning and data processing systems, to enable high-throughput quick defect detection. ③ Data-driven intelligent inspection. Create advanced defect detection algorithms based on deep learning technology, improving network architecture, optimizing algorithms, and data processing methods to enhance the accuracy and efficiency of defect identification and detection. ④ Defect causality analysis and modeling. Use ultra-high sensitivity defect detection technology to investigate the physical mechanisms behind defect formation and predict their potential impact on device performance, providing theoretical support for the design and improvement of high-precision machining processes.

Currently, this technology is continuously evolving towards higher sensitivity, higher resolution, faster inspection speeds, greater intelligence, and lower costs. The emergence of cutting-edge technologies such as advanced photonics, computational imaging, metasurfaces, and quantum sensing promises further improvements in defect detection sensitivity, resolution, and efficiency, offering new opportunities for the development of ultra-high sensitivity, cross-scale defect detection. As global high-end manufacturing continues to advance, ultra-high sensitivity, cross-scale defect detection technology will play an increasingly critical role in next-generation chip manufacturing, precision component processing, and other high-end manufacturing sectors.

(6) Intelligent scientific computing driven by data and physical laws

Intelligent science computing driven by data and physics is an emerging research paradigm that deeply integrates AI technologies, scientific computing methods, and physical laws to advance scientific research and technological applications. Jim Gray, the Turing Award laureate and pioneer of relational databases, proposed the four paradigms of scientific research in 2007: the first paradigm (physical experiments), the second paradigm (theoretical analysis), the third paradigm (scientific computing, represented by simulations), and the fourth paradigm (data-intensive science, represented by AI). However, intelligent scientific computing driven by data and physics is not merely a combination of these paradigms but represents a profound integration and innovation that constructs a novel framework for future-oriented research. This paradigm has revolutionized multiple key aspects of scientific research and computation: ① problem definition: extracting potential scientific problems from existing scientific data and clarifying research objectives, such as identifying areas for improving material properties; ② knowledge extraction and

embedding: using AI techniques like neural networks to extract physical laws from data, such as key patterns for density functional theory or embedding physical laws into neural networks; ③ hypothesis generation: leveraging generative models (e.g., diffusion models) to propose novel scientific hypotheses, thereby expanding scientific research boundaries, such as predicting new active compounds in drug development; ④ experimental validation: building automated experimental validation processes, for instance, seamlessly connecting data models with physical experiments through embodied robots; ⑤ result report and interpretability: interpreting the mechanisms and underlying laws behind predictions of complex models via experimental result visualization, natural language generation technologies, and model explain ability tools; ⑥ expert feedback and evolution: incorporating expert experience and knowledge to provide feedbacks for continuously optimizing models and hypotheses.

The future development of data and physics-driven intelligent scientific computing presents three main trends. ① Interdisciplinary integration to address key scientific problems: to tackle complex scientific challenges, interdisciplinary collaboration is increasingly important. By working closely with experts from various fields, it becomes possible to summarize a wealth of physical laws and expert knowledge, uncovering potential scientific issues that would otherwise remain hidden. ② Infrastructure development and the establishment of data platforms: with the rapid accumulation of data across various scientific domains, effectively collecting, processing, storing, and sharing these data has become a key issue in research. In the future, it will be crucial to build interdisciplinary, efficient data platforms that integrate data from diverse sources, enhancing research efficiency. ③ The “data–physics–knowledge–innovation” four-wheel-driven self-evolution system: current data-driven scientific computing faces challenges such as the lack of physical mechanisms, insufficient domain knowledge, and a heavy reliance on expert experience for design. Future research will focus on developing a self-evolving scientific computing system driven by “data–physics–knowledge–innovation”, combining machine learning, physical laws, and expert knowledge to promote self-learning and optimization of models. This self-evolution mechanism will improve computational accuracy and drive the generation and application of innovative theories.

(7) Distributed planning and intelligent cooperative control for large-scale satellite clusters

Distributed planning and intelligent cooperative control for large-scale satellite clusters refer to a technical domain that involves self-organizing collaborative mission planning, task allocation, and attitude-orbit control for large-scale satellite clusters within a distributed communication environment without reliance on centralized control nodes. This technology eliminates the dependency on single centralized management nodes such as ground stations, by fully using real-time perception, neighborhood interaction, autonomous negotiation, and autonomous control capabilities of satellite platforms. It achieves decentralized self-organized collaborative operation and tasks under conditions characterized by strong robustness, fast response times, and low operational costs, offering significant advantages in production costs, resilience against destruction, and on-orbit reconfiguration.

As satellite manufacturing, launch technologies advance and commercial spaceflight thrives, large-scale satellite constellations are becoming a new paradigm for executing space missions. Distributed planning and intelligent collaborative control provide the theoretical and methodological foundation for their efficient autonomous operations. Key research directions encompass distributed collaborative task planning and intelligent autonomous collaborative control for satellite clusters. The former addresses complexities like vast scales, diverse cooperative modes, intermittent communications, and dynamic task bursts in large-scale remote sensing satellite groups, studying multi-agent collective intelligence decision-making driven by multiple scenarios and distributed task scheduling methods to achieve efficient coordination and rapid responses for remote sensing observation tasks. The latter pertains to optimizing overall performance and task execution efficiency through intelligent techniques for coordinated operations among satellites or spacecraft regarding attitudes and orbits.

The absence of central nodes and global information presents theoretical challenges to distributed planning and intelligent collaborative control. Additionally, engineering practices of large-scale satellite cluster distributed planning and intelligent collaborative control face difficulties due to limitations such as physical characteristics of satellite platforms, spatial communication environments, and dynamically uncertain task requirements. The cutting-edge research focuses on four main areas: ① design of distributed planning and collaborative control system architecture, including mechanisms for selecting dynamic master nodes and hierarchical grouping strategies for satellite clusters, aiming to provide an engineering implementation

framework for planning and control; ② decentralized theories and methods for distributed autonomous collaborative decision-making, covering modeling of distributed decision problems, analysis of model validity, design of autonomous collaborative decision algorithms, and convergence analysis and assurance, providing a theoretical basis for task planning in large-scale satellite clusters; ③ large-scale swarm collaborative control methods based on bio-swarm intelligence and advanced intelligent technologies, achieving distributed self-organized collaborative control relying solely on neighbor-to-neighbor communications; ④ collaborative control theories and methods grounded in advanced AI technologies like large language models, leveraging their potent learning and inference capabilities for intelligent decision-making, enabling rapid responses to external changes and enhancing system robustness and adaptability.

(8) Ultra-large-scale integrated optical computing chips

Ultra-large-scale integrated optical computing is a novel computing paradigm that employs light as the fundamental carrier for information processing. It involves constructing large-scale integrated optical chips based on optical units and performing necessary optical operations to achieve data processing or computation. This approach leverages the high bandwidth, low latency, low power consumption, and parallelism of light, offering advantages such as high computational density, miniaturization, and stability. It is particularly suitable for handling complex specific tasks like AI and combinatorial optimization, marking an important direction in the development of new computing architectures.

Key research areas encompass photonic computing chips based on various structures including on-chip Mach-Zehnder interferometer (MZI) mesh networks, on-chip micro-ring resonator weight banks, on-chip diffractive metasurfaces, as well as other on-chip optical components like multimode interferometers and three-dimensional (3D) integrated waveguides. Each type of photonic computing chip has its own set of strengths and limitations. Currently, the application of photonic computing chips is not as widespread as electronic devices, with most studies still focusing on processing simple datasets and few practical applications.

The development of photonic computing faces challenges such as insufficient computational power, limited functionality, difficulties in dynamic computation, and low training efficiency, which constrain its practical implementation. Looking forward, photonic computing will primarily focus on optoelectronic intelligent hybrid computing architectures, requiring deeper exploration into: ① developing efficient optoelectronic hybrid parallel computing architectures; ② increasing the large-scale integration and scalability of photonic computing chips; ③ achieving optical nonlinear activation and dynamic reconfiguration; ④ creating algorithms, coding schemes, and computational theories dedicated to photonic computing; ⑤ enhancing the design, integration, and packaging capabilities of optoelectronic systems; ⑥ expanding and clarifying application scenarios that highlight the superiority of integrated optical computing.

The goal is to realize ultra-large-scale, high-performance, low-power, and reconfigurable photonic computing chips to meet the demands of complex computing tasks in the era of AI. Additionally, exploring fully optical architecture-based integrated optical computing technology must proceed concurrently and collaboratively.

(9) Theory and method of all-optical deep computational imaging

As the next generation of optoelectronic imaging technology, computational imaging fundamentally integrates information theory into conventional imaging. By incorporating information encoding and computational decoding, the limitations of conventional optical imaging can be overcome. Computational imaging has experienced the development stage from shallow understanding to deep exploration, from fragmented technological breakthroughs to systematic theoretical frameworks. At present, with the advancement of computing power and the development of AI, computational imaging has progressed into a stage of the systematic development of theory and methodology.

Intuitively, all-optical deep computational imaging typically refers to leveraging the interaction between light and matter to map the network computation processes onto an optical platform, completing specific computational imaging tasks. Its feature is to replace the conventional electronic computation with the optical computation. Optical information processing inherently results from large-scale parallel computations, aligning well with the characteristics of deep learning computational models. Compared

to electronic systems, optical systems offer higher bandwidth, which means optical devices that can compute at “light speed” require shorter response time. In addition, as passive computing devices, optical devices exhibit many advantages, such as parallel processing, low power consumption, and high-speed response.

From another perspective, the word “all-optical” in all-optical deep computational imaging also indicates the full optical field information, including intensity, phase, spectrum, and polarization, and the information utilization from low dimension to high dimension. Fully using the potential of “all-optical” information requires us to change from focusing on single-dimensional imaging modalities using such as spectrum or polarization, to deep exploration of multidimensional imaging paradigms. The process requires the support of advanced theories, like the propagation and detection of multi-dimensional optical field, and its joint computation. It will also drive the emergence of numerous computational imaging methods, for example AI-driven optical system design, bioinspired meta-vision detectors, low-cost ultra-large-aperture remote sensing cameras, and advanced imaging under extreme conditions.

All-optical deep computational imaging holds great promise in building advanced intelligent computing systems, promoting the development of new photonic computing paradigms, and leading computational imaging to a more efficient and intelligent future.

(10) Semantic communication theory and technology based on artificial intelligence

Semantic Communication refers to the method of extracting semantic information from a source, encoding it, transmitting it through a noisy channel, and then decoding it at the destination to reconstruct the original semantic meaning. Unlike traditional communication systems that require bit-level fidelity between encoded and decoded sequences, semantic communication only requires that the meaning of the semantic information received by the destination matches that sent by the source, significantly enhancing transmission efficiency. By deeply integrating communication and AI semantic communication transforms the design paradigm of communication systems under the guiding principle of “understand before communicate”. By employing intelligent information processing methods, it extracts semantically relevant information from raw data for transmission, thereby drastically reducing the volume of communication data and effectively improving both the efficiency and reliability of communications. Research indicates that semantic communication can achieve significant improvements in communication efficiency, reaching more than five times the effectiveness of existing syntactic communication methods in specific scenarios. The full potential performance of this technology remains to be further explored and promises new technical means for low signal-to-noise ratio (SNR) communication, interference-resistant communication, multimodal/cross-modal communication, and intelligent and concise communication.

The classic channel capacity limits have become a technological bottleneck constraining the enhancement of communication transmission and network performance. Expanding Shannon’s information theory from a semantic perspective and establishing an AI-based semantic communication theory and technology system is a research focus for future information and communication fields. Key research directions include the measurement of semantic information, construction of semantic knowledge bases, and semantic encoding and transmission among foundational theories and core methodologies. Measurement of semantic information forms the basis of semantic information theory, encompassing mathematical theories of semantic communication and the mathematical representation of semantics. A semantic knowledge base stands as a hallmark distinct from syntactic communication, serving as a structured knowledge network model with memory capabilities that provides related semantic knowledge descriptions for data information. Semantic encoding and transmission involve using neural networks or transform coding methods to extract semantic features from source sequences and map them into channel transmission symbols, achieving performance improvements through efficient semantic representation transmission.

Currently, AI-based semantic communication theory and technology research involves multiple aspects, primarily addressing the following challenges: ① efficient representation of semantic information for multimodal sources; ② elastic compression of semantic information under highly dynamic changes in communication environments and semantic task requirements; ③ collaborative transmission and overall optimization of semantic information under dynamic changes in the correlation between sender and receiver semantic knowledge bases; ④ development of self-reliant chips tailored to the computational demands of semantic information recognition, extraction, and reconstruction.

3.1.2 Interpretations for three key engineering research fronts

3.1.2.1 Basic theory and methodology of embodied intelligence

Embodied intelligence encompasses multiple aspects of morphology, motion, perception, and learning, exhibiting strong interdisciplinary and cutting-edge characteristics. It emphasizes the continuous learning of an agent during its interaction with the physical world, posing significant challenges to the intrinsic structure of agents and their computational models. In recent years, scholars from various countries have conducted in-depth research from different perspectives. Research advancements are primarily reflected in two dimensions: key technologies and system platforms.

In the dimension of key technologies, action learning methods such as reinforcement learning remain the most fundamental learning tools in the domain of embodied intelligence. The current focus is on enhancing the scalability and multitask learning capabilities of reinforcement learning, particularly by leveraging many heterogeneous tasks to strengthen its foundational role in embodied systems. Leading research institutions in this area include OpenAI, DeepMind, and Massachusetts Institute of Technology (MIT).

Building upon reinforcement learning, the embodiment of intelligent agents has garnered substantial attention in recent years, gradually becoming a research hotspot. This area focuses on using the features of an agent's morphology to offload computational resources (i.e., using the body to replace some brain functions), and achieving autonomous development and evolution of morphological structures (to enable automatic design). However, much of this work remains at the simulation validation stage. Key institutions involved in this research include Stanford University, UC Berkeley, Carnegie Mellon University, and Tsinghua University, among others.

Meanwhile, embodied sensing, as the channel for embodied intelligence to interact with the environment, has gained wide attention in real-time multimodal sensor-based perception interaction, data collection, and pre-training of multimodal embodied foundational models. Challenges such as sensor integration and modality integration persist when using visual sensors, large-area tactile skins, and fine visuotactile sensors for real-time interaction between embodied agents and their environments. Pre-training of multimodal embodied foundational models based on collected data via relevant sensors and simulation methods is still in its initial developmental phase. Prominent research institutions in this field include MIT, Stanford University, Tsinghua University, Peking University, Shanghai Jiao Tong University, Beijing University of Posts and Telecommunications, etc.

Additionally, the integration of embodied intelligence with robotic manipulation and navigation has become increasingly close. A notable trend in recent years is the introduction of language-guided active perception, such as visual language navigation, visual semantic navigation, visual language manipulation, and embodied question answering. These models have seen considerable development and have been validated in various physical environments. The current focus is on generalizing learning scenarios, while dynamic capabilities of scenes are less examined. Major research institutions in this direction include MIT, Georgia Tech, University of Technology Sydney, Shanghai Jiao Tong University, Tsinghua University, Peking University, ByteDance, etc.

In terms of system platforms, research includes three aspects: soft robotics, humanoid robots, and large embodied models.

1) Soft robotics are characterized by their flexibility, safety, and adaptability. Their compliance helps simplify control for completing necessary tasks in complex environments. Current research directions include soft intelligent materials, morphology design, actuation control, perception interaction, and modeling of full-coupled interactions between soft robots and their environment. Main research institutions include MIT, Harvard University, Tsinghua University, Huazhong University of Science and Technology, SRT Company, etc.

2) Humanoid robots aim to mimic human appearance and behavior to adapt to human social scenarios and assist in various activities but currently suffer from deficiencies in whole-body motion control algorithms, active environmental perception, and human-robot interaction. Current research focuses on multimodal fusion for perception and operation, human-machine emotional recognition interaction, etc. Leading research institutions include Optimus (Tesla), Boston Dynamics, CMU, Zhejiang

University, etc.

3) Large embodied models seek to combine the powerful cognitive abilities of large models with the physical interaction capabilities of embodied intelligence, allowing agents to better understand and adapt to complex real-world environments and achieve more intelligent and flexible decision-making and task execution. Research focuses on improving model generalization, interaction mechanisms between agents and the physical world, and addressing the hallucination problem in large models. Primary research institutions include Google, Microsoft, Huawei, Baidu, ByteDance, Tsinghua University, etc.

The main output countries of core papers in the front of “basic theory and methodology of embodied intelligence” are shown in Table 3.3. The USA ranks first in the number of core papers, accounting for 31.48% of the total, followed by China, which accounts for 23.70%, with an average publication time that is one and a half years later than that of the USA. Among the top ten institutions producing core papers (Table 3.4), four are from the USA and four are from China. As depicted in Figure 3.1, there is close cooperation among the major output countries; in terms of cooperation between major producing institutions (Figure 3.2), it primarily occurs among four institutions in the USA and two in China. In terms of countries with the greatest output of citing papers (Table 3.5), China takes the lead, accounting for approximately 40%, with the USA ranking second, and all other countries accounting for less than 10% each; among the top ten institutions with the greatest output of citing papers (Table 3.6), all are from China except for the Georgia Institute of Technology, ranked seventh, and the National University of Singapore, ranked eighth,

Table 3.3 Countries with the greatest output of core papers on “basic theory and methodology of embodied intelligence”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	85	31.48	7 766	91.36	2019.7
2	China	64	23.70	5 871	91.73	2021.1
3	UK	39	14.44	3 456	88.62	2020.1
4	Italy	32	11.85	2 599	81.22	2019.2
5	Germany	26	9.63	1 807	69.50	2019.8
6	France	16	5.93	1 050	65.62	2019.6
7	Australia	15	5.56	1 069	71.27	2020.3
8	Singapore	14	5.19	1 008	72.00	2019.7
9	Spain	13	4.81	979	75.31	2019.2
10	Switzerland	11	4.07	1 071	97.36	2019.9

Table 3.4 Institutions with the greatest output of core papers on “basic theory and methodology of embodied intelligence”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Bohai University	9	3.33	1 188	132.00	2022.2
2	Massachusetts Institute of Technology	8	2.96	1 198	149.75	2019.4
3	National University of Singapore	8	2.96	420	52.50	2020.4
4	Guangdong University of Technology	7	2.59	1 162	166.00	2021.6
5	Carnegie Mellon University	7	2.59	765	109.29	2019.6
6	South China University of Technology	7	2.59	582	83.14	2021.7
7	Italian Institute of Technology	6	2.22	371	61.83	2019.0
8	Cornell University	6	2.22	322	53.67	2019.7
9	University of California, San Diego	5	1.85	874	174.80	2020.2
10	Chinese Academy of Sciences	5	1.85	863	172.60	2019.4

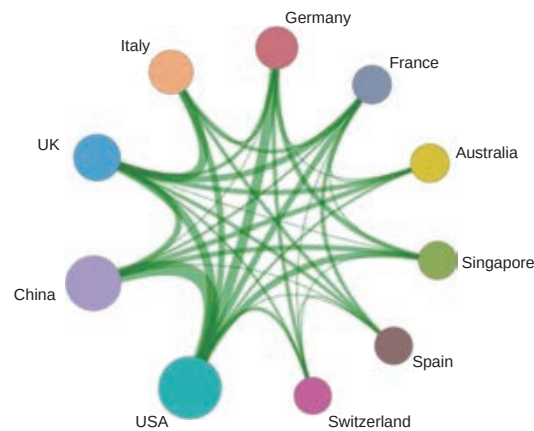


Figure 3.1 Collaboration network among major countries in the engineering research front of “basic theory and methodology of embodied intelligence”

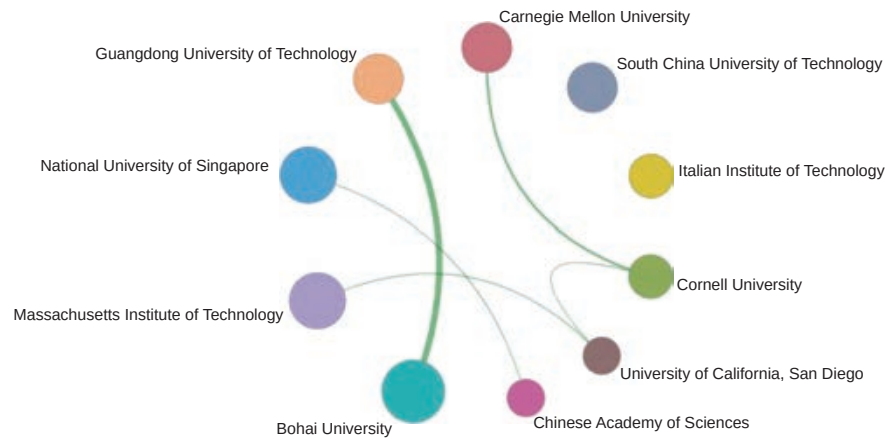


Figure 3.2 Collaboration network among major institutions in the engineering research front of “basic theory and methodology of embodied intelligence”

Table 3.5 Countries with the greatest output of citing papers on “basic theory and methodology of embodied intelligence”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	7 708	40.06	2022.3
2	USA	3 465	18.01	2022.0
3	UK	1 513	7.86	2022.0
4	Germany	1 264	6.57	2022.0
5	Italy	1 205	6.26	2021.9
6	Republic of Korea	877	4.56	2022.2
7	Japan	748	3.89	2022.0
8	Australia	641	3.33	2022.0
9	Spain	626	3.25	2022.0
10	Canada	621	3.23	2022.1

reflecting the high level of attention given to this topic by Chinese research institutions.

The key development directions for the fundamentals and methods of embodied intelligence over the next 5 to 10 years include (Figure 3.3):

- 1) Embodied collaboration: As current AI technologies advance towards general intelligence, embodied intelligence is widely recognized as a critical pathway to this goal. Given its intrinsic connection to physical entities, embodied intelligence must rely on the morphology and structure of the agent. Therefore, an important future direction is to collaborate different forms and capabilities of embodied intelligent agents to achieve cognitive emergence and collective efficiency.
- 2) Embodied learning: The essence of intelligence lies in continuous learning. Present research in embodied intelligence, influenced by large models, still has high demands for data and computational power. This contrasts with the paradigm of achieving sustained capability enhancement through physical interaction. Thus, efforts should focus on exploring how to leverage the morphology and behavior of embodied agents to realize continuous autonomous learning.
- 3) Humanoid robots: Embodied humanoid robots will redefine human-machine relationships. While current humanoid robots have seen improvements in basic capabilities such as perception and motion, their multimodal perception and motion strategy generation and control are loosely coupled, leading to insufficient environmental adaptability and dexterous manipulation skills. Consequently, further exploration is needed in developing humanoid robots that integrate embodied skills such as perception/navigation, motion control, and grasping/operation into a unified system.

Table 3.6 Institutions with the greatest output of citing papers on “basic theory and methodology of embodied intelligence”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	631	20.45	2022.0
2	Tsinghua University	288	9.33	2022.4
3	Zhejiang University	284	9.20	2022.3
4	Harbin Institute of Technology	276	8.94	2022.3
5	Northeastern University	256	8.30	2022.5
6	Shanghai Jiao Tong University	233	7.55	2022.3
7	Georgia Institute of Technology	230	7.45	2021.5
8	National University of Singapore	227	7.36	2021.8
9	Bohai University	224	7.26	2022.5
10	South China University of Technology	222	7.19	2022.3

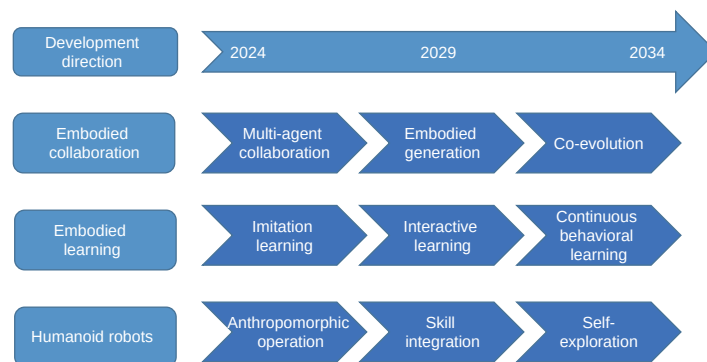


Figure 3.3 Roadmap of the engineering research front of “basic theory and methodology of embodied intelligence”

3.1.2.2 Theory and design of wafer-scale system-on-chip

Wafer-level system-on-chip (SoC) achieves the mapping of complex domain-specific applications onto wafer-level hardware through joint innovations in architecture design that integrates domain-specific software and hardware systems, along with high-density integration methods at the wafer level. This approach offers advantages such as high functional density, superior energy efficiency, and flexible application deployment. However, due to the large scale and complexity of resources in wafer-level SoCs, which heavily rely on advanced integration processes, achieving functional synergy between chiplets is challenging. Consequently, there is an urgent need for breakthroughs in both theoretical frameworks and manufacturing processes for wafer-level SoCs.

First, in terms of theoretical architecture, two main trends are emerging:

- 1) Deep integration of architecture design and application tasks: The proportion of general-purpose computing power designed for all-domain applications has been decreasing from 95% in 2016, projected to drop below 30% by 2030. Conversely, the share of intelligent computing power tailored for AI applications has rapidly increased from 3% in 2016, expected to exceed 70% by 2030. The design of intelligent computing system architectures remains deeply intertwined with the evolution of machine learning algorithms.
- 2) Software–hardware co-design: This includes co-design, co-simulation, co-execution, and co-evaluation. Compared to the decoupled implementation in general-purpose computing systems aimed at solving all computable problems across domains, the integrated software–hardware approach in specialized computing systems maximizes performance and efficiency for specific applications. Software–hardware co-design can significantly enhance overall computational capabilities while maintaining system flexibility.

Second, regarding process realization, key development directions include:

- 1) Wafer-level silicon substrate design and manufacturing: addressing the preparation challenges of wafer-level interconnect silicon substrates to expand the design space for heterogeneous integration systems.
- 2) High-density high-precision integration processes: initially focusing on overcoming the high-density bonding process for heterogeneous and hetero-material chiplets onto wafer-level silicon substrates, as well as high-density power delivery and cooling processes at the wafer level; subsequently, through cross-scale high-precision integration processes, ensuring reliable assembly from microsystems like wafers, power supply, and cooling systems into a cohesive whole.

Prominent research institutions in the field “theory and design of wafer-scale system-on-chip” include UCLA, University of Illinois, TSMC, Tsinghua University, Institute of Microelectronics of Chinese Academy of Sciences, and CEA-Leti in France.

The core papers in the engineering research front of “theory and design of wafer-scale system-on-chip” reveal that the USA leads in the output of core papers, accounting for approximately 45% of the total, with earlier average publication years (Table 3.7). China follows behind with approximately 29%, showing rapid progress but with an average publication time about one year later than the USA. Collaboration among countries is evident: China maintains cooperation with multiple countries, and there is particularly close collaboration among Germany, the UK, and Switzerland in Europe (Figure 3.4). Among the top ten institutions producing core papers, five are from the USA, four from China, and one from the Republic of Korea (Table 3.8). In terms of institutional collaboration, only two American institutions collaborate extensively (Figure 3.5). For citing papers, China leads with nearly half of the total, followed by the USA, while other countries account for less than 10% (Table 3.9). Among the top ten institutions with the greatest output of citing papers, except for the National University of Singapore ranking fifth, the rest are from China, highlighting the attention paid by Chinese research institutions to this topic (Table 3.10).

Over the past five years, significant research achievements have been made in the theory and design of wafer-level SoC. However, from the perspective of the entire field’s development, its application and research remain in the nascent stages, with numerous bottleneck issues that urgently need resolution. As illustrated in Figure 3.6, the key development directions for the next 5 to 10 years encompass the following five areas:

- 1) Domain-specific software–hardware co-design architecture. Wafer-level SoCs exhibit notable characteristics and advantages

Table 3.7 Countries with the greatest output of core papers on “theory and design of wafer-scale system-on-chip”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	63	44.68	2 882	45.75	2020.9
2	China	41	29.08	1 218	29.71	2021.8
3	Republic of Korea	15	10.64	1 239	82.60	2021.0
4	Switzerland	8	5.67	966	120.75	2022.4
5	Germany	7	4.96	896	128.00	2021.4
6	UK	4	2.84	882	220.50	2022.2
7	Belgium	4	2.84	304	76.00	2022.2
8	Singapore	4	2.84	235	58.75	2022.5
9	Canada	4	2.84	15	3.75	2021.2
10	India	3	2.13	61	20.33	2022.3

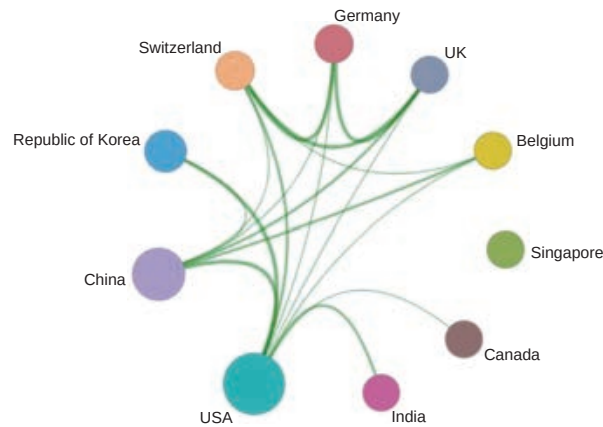


Figure 3.4 Collaboration network among major countries in the engineering research front of “theory and design of wafer-scale system-on-chip”

Table 3.8 Institutions with the greatest output of core papers on “theory and design of wafer-scale system-on-chip”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of California, Los Angeles	14	9.93	1 030	73.57	2020.5
2	Fudan University	6	4.26	179	29.83	2022.0
3	University of California, San Diego	6	4.26	122	20.33	2020.8
4	Peking University	5	3.55	303	60.60	2021.4
5	Chinese Academy of Sciences	5	3.55	207	41.40	2021.8
6	University of Illinois	5	3.55	127	25.40	2020.4
7	Cerebras Systems	5	3.55	23	4.60	2021.4
8	The Pennsylvania State University	4	2.84	76	19.00	2022.2
9	Korea Advanced Institute of Science and Technology	4	2.84	46	11.50	2022.2
10	Zhejiang Lab	4	2.84	4	1.00	2023.0

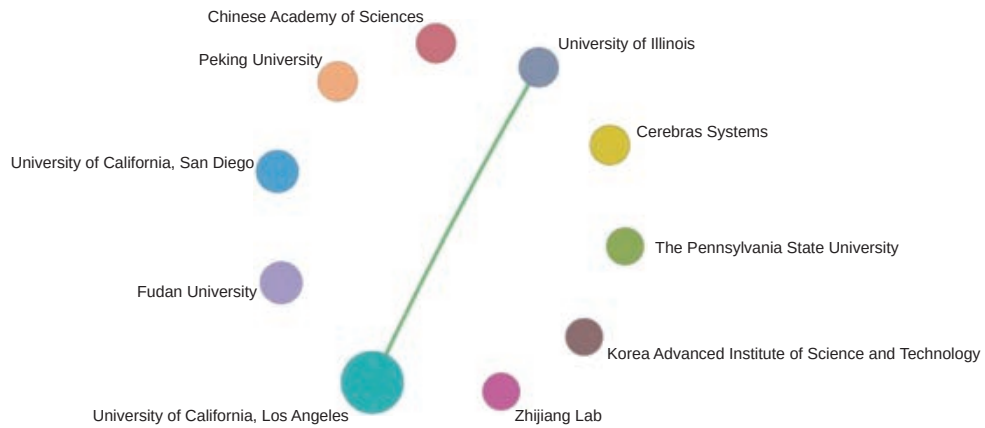


Figure 3.5 Collaboration network among major institutions in the engineering research front of “theory and design of wafer-scale system-on-chip”

Table 3.9 Countries with the greatest output of citing papers on “theory and design of wafer-scale system-on-chip”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 334	49.48	2022.3
2	USA	796	16.88	2022.2
3	Republic of Korea	413	8.76	2022.2
4	Germany	204	4.32	2022.5
5	Singapore	194	4.11	2022.3
6	Japan	163	3.46	2022.2
7	UK	158	3.35	2022.4
8	India	140	2.97	2022.6
9	France	117	2.48	2022.2
10	Canada	107	2.27	2022.2

Table 3.10 Institutions with the greatest output of citing papers on “theory and design of wafer-scale system-on-chip”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	410	29.10	2022.3
2	Tsinghua University	161	11.43	2022.4
3	Zhejiang University	120	8.52	2022.6
4	Fudan University	108	7.67	2022.4
5	National University of Singapore	107	7.59	2022.3
6	Peking University	102	7.24	2022.3
7	Nanjing University	96	6.81	2022.2
8	Shanghai Jiao Tong University	85	6.03	2022.4
9	Huazhong University of Science and Technology	77	5.46	2022.4
10	University of Electronic Science and Technology of China	76	5.39	2022.4

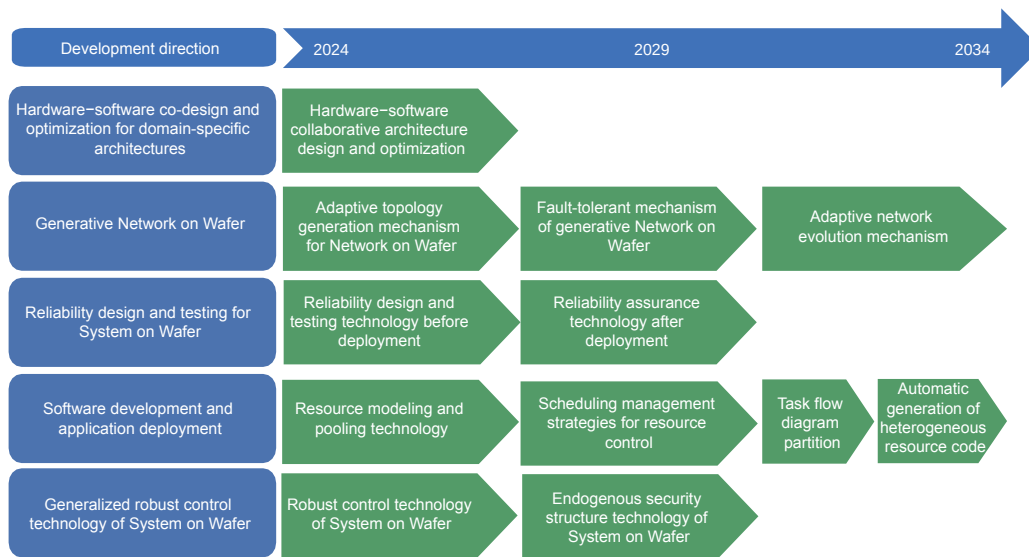


Figure 3.6 Roadmap of the engineering research front of “theory and design of wafer-scale system-on-chip”

such as large-scale, high-density integration of computational and storage resources, and low-latency, high-bandwidth transmission capabilities between heterogeneous resources. These features provide vast exploration space for constructing computing architectures tailored to different applications, while also posing significant challenges for the design and optimization of domain-specific software–hardware co-design architectures.

2) Generative on-wafer interconnection network technology. High-density, highly adaptable on-wafer interconnection networks are crucial for the functionality, performance, and efficiency of wafer-level SoCs. Generative on-wafer interconnection networks must not only achieve far greater density and scale than existing connection networks but also offer high flexibility and adaptability. Therefore, future research must focus on key technologies such as adaptive network topology generation mechanisms, multi-dimensional fault-tolerance mechanisms for generative networks, and adaptive network evolution mechanisms, to enable software-defined application services and support the self-evolution of wafer-level SoCs.

3) Reliability design and testing of wafer-level SoCs. Given the high-density integration architecture and highly dynamic application structures, pre-operational reliability design and testing, as well as operational reliability assurance, are critical for wafer-level SoCs. Future research directions include reliability design techniques for wafer-level substrates, cross-scale high-precision, high-reliability integration technologies, high-reliability power delivery and cooling technologies at the wafer level, and wafer-level reliability testing and self-regulation technologies.

4) Software tool development and application deployment optimization. The diverse combinations of large-scale, high-density integrated resources and their adaptation to application tasks in wafer-level SoCs represent NP-hard problems. To fully leverage the advantages of wafer-level SoCs and optimize application deployment, future research priorities will include: ① modeling and pooling methods for large-scale, high-density integrated resources in wafer-level SoCs; ② management scheduling strategies that support resource combinations and changes; ③ methods for reasonably partitioning task graphs to use the bandwidth advantages of wafer-level SoCs; ④ automated code generation methods for heterogeneous resources in wafer-level SoCs.

5) Generalized robustness technology for systems. As wafer-level SoCs designed for various domain-specific applications increase, uncertainties leading to system robustness issues, security concerns inherited from heterogeneous chiplets, and security challenges arising from separate manufacturing processes will become more severe. Consequently, generalized robustness control technology for wafer-level SoCs will attract increasing attention. Future research will focus on how to construct secure architectures at the system level based on untrusted chiplets while maintaining high system performance. Key research areas

will include wafer-level system security chip architectures and hardware defense technologies, such as building intrinsic security structures and performing software–hardware co-optimization under security attributes.

3.1.2.3 Low-altitude information network system and integrated sensing and communication technology

The low-altitude information network system and integrated sensing and communication (ISAC) technology represents core technologies for constructing future intelligent airspace infrastructure. The goal is to enhance the intelligent management capabilities and service levels of low-altitude airspace through deep integration of communication and sensing. Early research on low-altitude information networks primarily focused on military and emergency communication scenarios, concentrating on collaboration between diverse heterogeneous nodes such as swarms of low-altitude drones and ground networks to provide dynamic and reliable communication network access. As research has progressed, the scope has expanded from early single-function communication systems to drone networks with basic sensing capabilities, and now towards an intelligent network system that integrates communication, sensing, computation, and intelligence while sharing resources. The transition signifies a shift from fragmented to integrated systems and from single-function to multi-task collaborative operations. Recently, breakthroughs in ISAC have led to ground-based station systems equipped with large-scale antenna arrays providing communication and sensing services for low-altitude airspace, becoming a focal point of low-altitude information network research. Chinese governmental policies promoting low-altitude economic development have further propelled this direction, while global mobile communication equipment manufacturers and Chinese operators have initiated field trials involving hundreds of 5G-A base stations for low-altitude economy scenarios, extending applications to maritime routes and river navigation supervision, ground traffic regulation, bridge micro-deformation detection, and more.

Research directions in low-altitude information network systems and ISAC technology include communication-assisted sensing and sensing-assisted communication. First, in terms of communication-assisted sensing, it leverages communication systems not only for information transmission but also by sharing signal characteristics (e.g., propagation delay, direction information, and signal strength) to assist in sensing tasks, achieving cost-effective and efficient ubiquitous sensing. Given the extensive coverage and rapid changes in targets and environments within low-altitude networks, using existing communication infrastructures can ensure broad, real-time environmental sensing. Expanding from single-station to multi-station collaborative sensing enhances the range and accuracy of sensing through cooperation among multiple communication nodes, sharing information and resources. Second, for sensing-assisted communication, it focuses on using environmental information obtained via sensing systems such as target speed, position, delay, and angle, to aid the operation of communication systems. It optimizes spectrum allocation, adjusts signal transmission power, manages interference sources, and improves communication quality, reducing interruptions and interferences. In the highly dynamic environment of low-altitude information networks, sensing-assisted communication not only boosts performance but also enhances network adaptability by dynamically sensing environmental changes and target behaviors, adjusting communication strategies in real-time for more efficient, reliable, and robust services.

The main output countries of core papers in the front of “low-altitude information network system and integrated sensing and communication technology” are shown in Table 3.11. China leads in the number of core papers, accounting for approximately 78% of the total, followed by the USA, Australia, and the UK, with the latter having the highest citation per paper. Close collaborations exist between China, the UK, Australia, the USA, and Germany (Figure 3.7). Among the top ten institutions producing core papers, seven are from China (Table 3.12). University College London collaborates with seven institutions, while Southern University of Science and Technology and University of Technology Sydney collaborate with six and five institutions respectively, The University of New South Wales, Shanghai Jiao Tong University, and Beijing Institute of Technology collaborate with four institutions each (Figure 3.8). In terms of countries with the greatest output of citing papers, China ranks first with 48.24%, followed by the UK and the USA (Table 3.13). Among the top ten institutions with the greatest output of citing papers, nine are from China, underscoring the significant attention paid to this front by Chinese research institutions (Table 3.14).

The key development directions for low-altitude information network systems and ISAC technology over the next 5 to 10 years (Figure 3.9) include:

Table 3.11 Countries with the greatest output of core papers on “low-altitude information network system and integrated sensing and communication technology”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	49	77.78	4 268	87.10	2021.7
2	USA	17	26.98	1 571	92.41	2021.6
3	Australia	14	22.22	1 340	95.71	2021.6
4	UK	12	19.05	1 855	154.58	2021.9
5	Germany	7	11.10	643	91.86	2022.0
6	France	5	7.94	298	59.60	2021.8
7	Canada	4	6.35	345	86.25	2022.2
8	Finland	4	6.35	324	81.00	2021.0
9	United Arab Emirates	3	4.76	177	59.00	2022.3
10	Singapore	3	4.76	174	58.00	2022.0

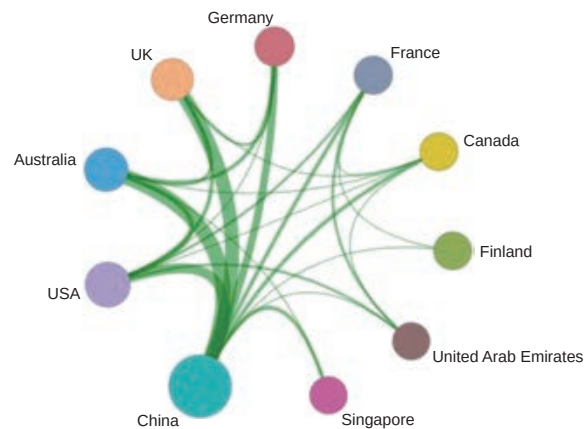


Figure 3.7 Collaboration network among major countries in the engineering research front of “low-altitude information network system and integrated sensing and communication technology”

Table 3.12 Institutions with the greatest output of core papers on “low-altitude information network system and integrated sensing and communication technology”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Beijing University of Posts and Telecommunications	9	14.29	918	102.00	2021.7
2	Southern University of Science and Technology	8	12.70	937	117.12	2022.1
3	The University of New South Wales	8	12.70	648	81.00	2021.6
4	University College London	7	11.11	1 053	150.43	2022.1
5	Dalian University of Technology	5	7.94	783	156.60	2021.0
6	University of Technology Sydney	5	7.94	734	146.80	2020.6
7	Zhejiang University	5	7.94	677	135.40	2021.6
8	Shanghai Jiao Tong University	5	7.94	355	71.00	2022.4
9	Beijing Institute of Technology	4	6.35	287	71.75	2022.2
10	University of Macau	4	6.35	263	65.75	2022.5

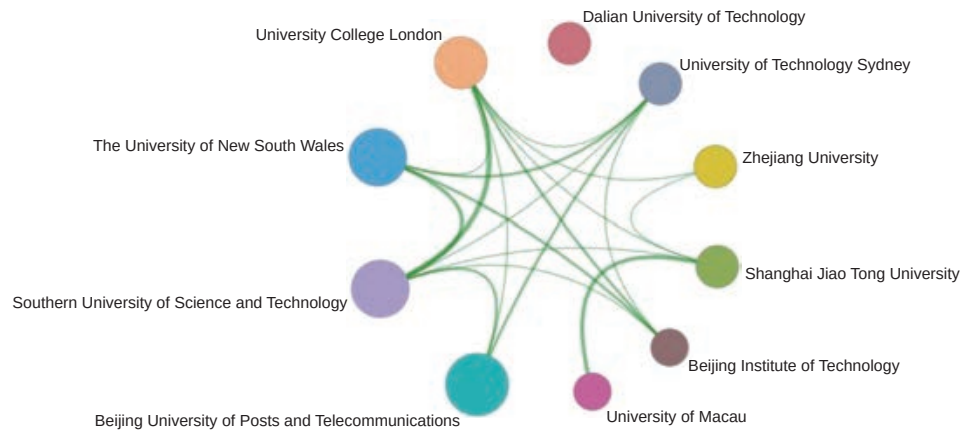


Figure 3.8 Collaboration network among major institutions in the engineering research front of “low-altitude information network system and integrated sensing and communication technology”

Table 3.13 Countries with the greatest output of citing papers on “low-altitude information network system and integrated sensing and communication technology”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 073	48.24	2022.6
2	UK	416	9.68	2022.5
3	USA	414	9.63	2022.4
4	Canada	221	5.14	2022.5
5	Australia	215	5.00	2022.3
6	Republic of Korea	209	4.86	2022.6
7	Germany	201	4.68	2022.6
8	Singapore	167	3.89	2022.7
9	India	137	3.19	2022.5
10	Italy	136	3.16	2022.6

Table 3.14 Institutions with the greatest output of citing papers on “low-altitude information network system and integrated sensing and communication technology”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Beijing University of Posts and Telecommunications	249	17.88	2022.7
2	Southeast University	199	14.29	2022.6
3	University of Electronic Science and Technology of China	143	10.27	2022.7
4	Xidian University	127	9.12	2022.6
5	Zhejiang University	116	8.33	2022.9
6	Southern University of Science and Technology	105	7.54	2022.7
7	Beijing Institute of Technology	104	7.47	2022.6
8	Nanyang Technological University	95	6.82	2022.7
9	Shanghai Jiao Tong University	89	6.39	2022.7
10	Tsinghua University	84	6.03	2022.5

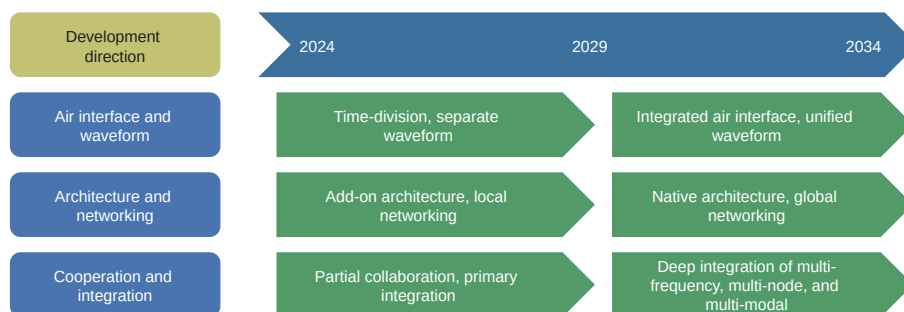


Figure 3.9 Roadmap of the engineering research front of “low-altitude information network system and integrated sensing and communication technology”

1) Air interface and waveform: Achieving sensing capabilities within the air interface of wireless communication systems is a fundamental aspect of developing ISAC technology. In the early stages of future development, communication and sensing waveforms will be relatively independent, using time division, frequency division, or spatial division methods to achieve their respective functionalities. Moving forward, the trend will be towards an integrated air interface where communication and sensing share a unified waveform, leading to deeper integration. This evolution will significantly enhance spectral utilization and overall performance in both sensing and communication.

2) Architecture and networking: The network architecture and multi-station networking are crucial development directions for low-altitude information networks and ISAC. Initially, add-on and plug-in designs for sensing network elements can be implemented on existing communication network architectures, establishing localized networks in key areas to provide low-altitude information services. In the long term, through natively integrated design, a deep fusion of communication and sensing will lead to an inherent architecture that supports global networking, ultimately forming a seamless coverage low-altitude information network.

3) Cooperation and integration: Multi-dimensional collaboration and deep information fusion are essential for achieving high-performance low-altitude information networks and ISAC. Initial efforts can focus on data-level fusion from single dimensions such as multi-band collaboration, multi-node collaboration, and multi-modal collaboration, processing local information. As technology advances, future developments will realize multi-dimensional deep fusion across multiple frequencies, multiple nodes, and multiple modes, enabling feature extraction and information fusion at a broader scale, thereby enhancing overall system performance.

3.2 Engineering development fronts

3.2.1 Trends in the Top 10 engineering development fronts

The Top 10 engineering development fronts in the information and electronic engineering field are summarized in Table 3.15, encompassing the subfields of electronic science and technology, optical engineering and technology, instrument science and technology, information and communication engineering, computer science and technology, and control science. Among these, “intelligent computing technology based on large domain models”, “high-performance compute-in-memory chip based on novel non-volatile memory”, and “industrial super-resolution optical microscope” are identified as fronts through both data mining and expert nomination, while the remainder are fronts nominated by experts. The annual number of core patents published for the Top 10 engineering development fronts from 2018 to 2023 is listed in Table 3.16.

(1) Integrated intelligent remote sensing monitoring technology for air-space-ground-sea

Integrated intelligent remote sensing monitoring technology for air-space-ground-sea combines multiple observation platforms—

Table 3.15 Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Integrated intelligent remote sensing monitoring technology for air-space-ground-sea	955	4 065	4.26	2021.0
2	Wafer-level bonding technology for heterogeneous integration	561	2 042	3.64	2021.0
3	Intelligent computing technology based on large domain models	938	5 843	6.23	2021.3
4	Design, manufacturing, and testing of large-scale high-precision metasurface devices	864	4 254	4.92	2020.8
5	High-performance compute-in-memory chip based on novel non-volatile memory	794	6 333	7.98	2020.8
6	Precise control technology for medical micro/nano robots	689	6 676	9.69	2020.6
7	Industrial super-resolution optical microscope	179	682	3.81	2020.5
8	Digital twin system based on hybrid modeling	969	4 864	5.02	2021.5
9	Security testing and evaluation technology for artificial intelligence	1 568	6 517	4.16	2021.4
10	Integration technology of satellite, cloud, computing, and network	218	1 991	9.13	2021.4

Table 3.16 Annual number of core patents published for the Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Integrated intelligent remote sensing monitoring technology for air-space-ground-sea	111	113	142	156	205	228
2	Wafer-level bonding technology for heterogeneous integration	45	72	99	92	106	147
3	Intelligent computing technology based on large domain models	49	68	147	225	214	235
4	Design, manufacturing, and testing of large-scale high-precision metasurface devices	79	97	152	234	201	101
5	High-performance compute-in-memory chip based on novel non-volatile memory	78	153	107	134	144	178
6	Precise control technology for medical micro/nano robots	93	103	131	129	124	109
7	Industrial super-resolution optical microscope	25	33	32	28	35	26
8	Digital twin system based on hybrid modeling	42	73	114	178	301	261
9	Security testing and evaluation technology for artificial intelligence	83	139	207	265	333	541
10	Integration technology of satellite, cloud, computing, and network	16	23	19	28	70	62

spaceborne, airborne, ground-based, and maritime—along with diverse imaging and non-imaging sensing modalities, including optical, radar, and ultrasonic. By leveraging AI, information processing, big data, and other technologies, this approach enables comprehensive monitoring and detection of objects of interest across spatial domains, temporal scales, dimensions, and granularities with high precision. It promotes collaborative information acquisition, automated information processing, and intelligent service applications, finding extensive application in national economic development and security. This technology eliminates the information silos of remote sensing observation data, overcoming limitations of single-sensor and single-detection systems in terms of spatiotemporal coverage, response time, observation granularity, and accuracy. By leveraging integrated intelligent information processing and applications of multi-source data, it shifts from traditional manual interpretation reliant on expert experience to autonomous reasoning based on intelligent technologies. This removes the constraints of “human-in-the-loop” operations and individual cognitive differences, achieving full-process, comprehensive intelligent support from information

acquisition to dynamic response. It ensures real-time, precise information assurance for defense security, reconnaissance surveillance, resource exploration, disaster warning, ecological protection, and other military-civilian sectors, serving as a core enabler of system energy aggregation, empowerment, and application.

The key technical directions include: ① multi-domain multi-mode remote sensing data acquisition, which involves the use of both imaging and non-imaging sensing modalities such as optical, radar, and ultrasonic to obtain high-quality multi-source data from space, air, ground, and sea; ② multi-source data mining and fusion processing, which entails the normalization of regularizing heterogeneous data from different platforms and sensors, uncovering correlations and hierarchical features within vast datasets, establishing high-order stereoscopic representation models for monitored environments across all spatiotemporal dimensions, and achieving integrated fusion processing using multimodal embedding, semantic analysis, knowledge graphs, and other techniques; ③ task-oriented multi-source heterogeneous resource integration, which systematically combines isolated and spatiotemporally dispersed detection resources to construct a task node network across domains, sources, and modalities, enabling precise control and dynamic scheduling of global resources for tasks, thereby enhancing response efficiency and execution capabilities; ④ autonomous generation of multi-dimensional data products across domains, which constructs self-learning decision models using large model generation and causal inference technologies to achieve an upgrade from supporting information analysis to autonomous reasoning, facilitating autonomous data generation, intelligent decision-making, and high-precision simulations in complex scenarios.

Since the early 21st century, China has made remarkable strides in remote sensing technology, gradually establishing a monitoring system characterized by multi-platform collaboration and multimodal integration. This encompasses satellites, unmanned (and manned) aircraft, ground sensors, and maritime platforms, achieving multi-layered perception capabilities ranging from low-resolution to high-resolution and from broad-area coverage to precise insight. Particularly, AI technology has permeated all levels of remote sensing monitoring information acquisition, processing, and application, further driving the development of remote sensing monitoring technology. Looking ahead, the development of integrated air-space-ground-sea intelligent remote sensing monitoring technology has evolved from single-domain detection to multi-domain coordination, from passive response to autonomous cognition, and from the observation of geophysical objects to human activity monitoring, while striving for further advancements in multi-domain collaboration, comprehensive understanding, dynamic response, and intelligent reasoning cognition". Through real-time digital mapping of physical information and dynamic changes in the real world, it aims to create a globally "dynamic" detection map, a "pervasive" physical domain, and a set of "reasoning" evolutionary indicators, ensuring comprehensive assurance for real-time monitoring, emergency response, predictive analysis, and integrated decision-making in complex environments.

(2) Wafer-level bonding technology for heterogeneous integration

Wafer-level bonding technology for heterogeneous integration, within the semiconductor manufacturing process, refers to the technique of directly bonding wafers made from different materials or with distinct properties using specific processes such as wafer-to-wafer (W2W), die-to-wafer (D2W), hybrid bonding (HB), and through-silicon vias (TSV). In today's era of information explosion, the demand for data processing capabilities and transmission speeds is continuously increasing, making traditional single-material chips insufficient to meet these requirements. This heterogeneous integration technology allows for the high-precision and high-strength connection of materials with diverse physical properties and functionalities. It enables the integration of multiple functions—such as computing, sensing, and communication—onto a single chip, significantly increasing the functional density and performance of the chip and achieving a leap in chip performance. Consequently, it not only accelerates the rapid development of fields like high-performance computing, high-speed communications, and intelligent sensing, but also provides new possibilities for the research and development of novel electronic products.

The key technical directions include direct bonding, metallic interconnect bonding, eutectic bonding, and polymer bonding. The technology is advancing towards higher precision (sub-micron level), lower cost, and larger-scale production (multi-die, system-level). Moreover, with the continuous discovery and application of new materials such as two-dimensional materials and ultra-wide bandgap semiconductors, the scope of application for heterogeneous integration technology will expand further. This

promises a more significant role in future information technology domains, potentially revolutionizing how advanced electronic systems are designed and manufactured.

(3) Intelligent computing technology based on large domain models

Intelligent computing technology based on large domain models refers to the application of large models within specific professional fields, enabling these models to possess both general knowledge and specialized domain expertise. This empowers industries across various sectors with advanced computational capabilities, driving continuous innovation and development. The emergence of killer applications based on large model technologies, such as ChatGPT, Sora, ERNIE Bot, and Qwen, has led to an increasingly deep penetration of large models into vertical domains like healthcare, finance, law, government services, and scientific research.

The key technical directions include: ① Domain pre-training: Building upon a general-purpose large model, this approach involves constructing high-quality domain-specific corpora to pre-train the model, equipping it with domain-specific knowledge. ② Domain fine-tuning: Tailored for specific tasks within professional fields, this method employs instruction fine-tuning, parameter-efficient fine-tuning, and reinforcement fine-tuning to enhance the model's performance in executing professional domain tasks more effectively and efficiently. ③ Knowledge base retrieval augmentation: Addressing issues of missing or outdated domain-specific knowledge, this technique involves building external knowledge bases to augment the performance of large models in professional fields through retrieval enhancement. ④ Hallucination evaluation and mitigation: Targeting the hallucination problem in large models, this direction uses methods such as retrieval augmentation and consistency evaluation to assess and mitigate hallucinations, ensuring that the generated content is reliable and safe in open-world scenarios.

As the application of domain-specific large models progresses, there is a need for in-depth research into efficient and high-quality external tools and external knowledge base invocation techniques to improve the specialized knowledge capability, timeliness, and hallucination mitigation of domain models. Additionally, research must focus on lightweight design of large model architectures and co-optimization of intelligent computing software and hardware to enhance accessibility, efficiency, and real-time performance of large model services. Furthermore, the technology will evolve towards greater intelligence and interpretability, necessitating exploration into advanced fine-tuning techniques based on chain-of-thought and beyond, such as causal reasoning and counterfactual analysis, to achieve higher efficiency in large model fine-tuning.

(4) Design, manufacturing, and testing of large-scale high-precision metasurface devices

The field of optics relies on gaining control over light flows. Metasurface consists of artificially engineered arrays of electromagnetic structures organized in periodic or quasi-periodic planar patterns at the subwavelength scale. Beneficial from the manipulating capability of the amplitude, phase, and polarization of incident light at subwavelength scale, metasurfaces not only have the potential to supplant traditional optical components, but also are highly promising for applications in super-resolution imaging, augmented reality AR, holography, vortex beam generation, nonlinear optics, diffractive optical neural networks, optical detector, and sensors, etc. Therefore, metasurface is recognized as “one of the ten key scientific breakthroughs in 21st century” and has attracted considerable attention worldwide.

In 2011, metasurface was experimentally verified, and then the research on metasurface has achieved great success. Despite these effects, however, one key challenge for the realization of applications for metasurface is how to design, fabricate, and detect large-scale, uniform meta-structures with high resolution. From the modeling perspective, machine learning has been emerging as an exciting tool for optimizing the design of metasurface. Various theories, such as topological metasurface, bound states in the continuum (BIC), and exceptional points, are intriguing for future design of metasurfaces.

On the nanofabrication perspective, the fabrication of metasurface is a COMS-compatible process. Many fabrication techniques used in semiconductor industries, such as e-beam lithography, focused ion beam lithography, laser direct writing, and nanoimprint, can be applied to the manufacturing of metasurfaces. However, the low throughput, high cost, and low uniformity of the available fabrication technique still hinder the commercialization of metasurfaces. Novel fabrication and detection

methods with high resolution, large writing area, low cost, short fabrication time, and better material compatibility are the key for metasurface development.

(5) High-performance compute-in-memory chip based on novel non-volatile memory

High-performance compute-in-memory (CIM) chips based on novel non-volatile memory (NVM) integrate computational capabilities into new storage devices, achieving high integration with other circuit components through scaled integration. This technology aims to break the traditional von Neumann architecture's separation of memory and computation, overcoming the power wall bottleneck in current systems. As foundational root technologies, existing high-speed dynamic random access memory (DRAM) and traditional non-volatile flash memory dominate the mainstream storage market due to their low manufacturing costs. However, DRAM's volatility and the low speed of traditional flash limit the development of CIM architectures. Emerging storage technologies such as resistive random access memory (RRAM) have achieved a certain balance between high speed and non-volatility, but they still face challenges like device stability. Through material and mechanism innovations, new types of non-volatile flash memory have broken through speed barriers while offering low power consumption and multi-bit storage, providing crucial support for building high-performance CIM chips. These chips promise to reshape future computing architectures and fully unleash system energy efficiency potential.

Key technological directions include: ① Storage medium optimization: Enhancing device and chip performance by developing lower power, higher read/write speed, and better durability non-volatile storage materials. Additionally, advancing 3D integration processes that stack multiple layers of storage cells vertically to increase storage density and parallelism, thereby improving chip energy efficiency and computing power. ② Innovative computing architecture: Inspired by biological brain neurons and synapses, designing compute-in-memory architectures that mimic human brain information processing for highly parallel, adaptive, and low-power computing suitable for AI and cognitive computing fields. ③ Precision and energy efficiency improvement: Optimizing read/write precision of storage units, design of computing circuits, and algorithm improvements to minimize computational errors and enhance accuracy of results. Concurrently, implementing low-power designs from the device, circuit, to architecture levels to reduce system energy consumption. ④ Algorithm and software synergy: Developing specialized computing algorithms and data storage formats tailored to CIM chips to maximize architectural advantages. Establishing a comprehensive software ecosystem, including compilers, development tools, operating systems, and applications, to promote the widespread adoption of CIM technology.

High-performance CIM chips based on novel NVM are evolving multidimensionally. Technically, there is continuous improvement in precision and energy efficiency, increasing integration density, enhanced multi-algorithm compatibility, and programmability to meet various complex scenario requirements. In terms of application, they are accelerating deployment in edge computing scenarios and gradually advancing into large-scale general-purpose computing domains. The industry's development momentum is robust, with increasingly fierce corporate competition, a maturing ecosystem, and ever-closer collaboration among academia, research institutes, and enterprises. Meanwhile, security and reliability receive significant attention, with ongoing optimization of reliability design and reinforcement of security protection functions to ensure stable and secure operation of chips across different scenarios.

(6) Precise control technology for medical micro/nano robots

Micro/nano robots are robotic devices with functional or characteristic dimensions below the sub-millimeter level, categorized into micro/nano manipulation robots and micro/nano swimming robots. Medical micro/nano robots are designed for biomedical research and clinical applications, aiming to achieve precise control, micro/nano manipulation, targeted drug delivery, and other operational tasks in both *in vitro* and *in vivo* environments.

The primary technological directions for precise manipulation techniques of medical micro/nano robots include: ① Cell manipulation: Using micro/nano robots for multi-feature detection of cells, assisting in cloning, constructing cell microenvironments, and more. ② Vascular clearance: Leveraging the small size of micro/nano robots to navigate them into microvessels that are difficult to reach with other surgical instruments, facilitating thrombolysis. ③ Targeted drug delivery:

Loading drug molecules onto micro/nano robots and guiding clusters of these robots using external fields (magnetic, chemical, optical, etc.) to move toward disease sites within the body, where they release the drugs to treat conditions such as tumors.

Research on micro/nano robots in the medical field is expanding, with this technology holding immense potential for development and application, promising significant advancements in precision medicine. However, the performance of current medical micro/nano robots requires improvement. First, micro/nano robots must exhibit excellent biocompatibility; for *in vivo* treatments, it is necessary to develop retrieval technologies for these robots or ensure they possess biodegradable properties. Second, real-time positioning and microscopic visual servo control present challenges that need to be addressed by closely integrating the latest imaging technologies and novel imaging equipment from the medical field. Lastly, the efficacy of micro/nano robot-targeted drug delivery needs verification from multiple perspectives, accelerating the transition from large animal experiments to clinical trials.

(7) Industrial super-resolution optical microscope

Industrial super-resolution microscopes have overcome the limitations of traditional optical microscopy, surpassing the traditional optical diffraction limit to achieve nanometer-level resolution, thereby providing humans with the ability to observe the microscopic world with greater precision. Unlike the limited resolution in classical microscopes, industrial super-resolution microscopes significantly enhance imaging resolution and detail capture capabilities through physical and chemical methods, allowing for the observation of finer biological structures and material characteristics. The main technological directions of industrial super-resolution microscopes currently include structured illumination microscopy (SIM), stimulated emission depletion microscopy (STED), photo-activated localization microscopy (PALM), and stochastic optical reconstruction microscopy (STORM), with the core being the enhancement of imaging resolution through specific illumination patterns and image processing algorithms.

Industrial super-resolution optical microscopes are evolving towards faster, deeper, wider field of view, and multidimensional development. For instance, by integrating adaptive optics and multiphoton excitation technologies, imaging depth can be increased. At the same time, through deep learning and algorithm optimization, super-resolution technology shows great potential in multidimensional multiplexing. Currently, the application of fast beam scanners makes STED microscopes one of the fastest super-resolution imaging technologies, as they do not require post-acquisition data processing. STORM microscopes can be combined with AX/AR confocal microscopes, featuring a newly reconstructed scanning head with a resolution of 8K×8K, ultra-fast resonant scanning, and the world's largest 25 mm field of view, reducing phototoxicity to specimens and minimizing specimen damage. Additionally, the use of near-field scanning optical microscopy (NSOM), superlenses and microsphere, which allow more evanescent waves to participate in imaging, is also a hot direction for technological development. With continuous technological advancements, industrial super-resolution optical microscopes will play an increasingly important role in fields such as biomedicine, materials science, nano-optical observation of minerals, semiconductor chip inspection, and graphene CVD detection, becoming a crucial tool for promoting industrial precision inspection and scientific research.

(8) Digital twin system based on hybrid modeling

A digital twin system based on hybrid modeling integrates data-driven and physical modeling, leveraging the explainability and generalization capabilities of mechanistic simulation and the flexibility and learnability of data-driven models to create a digital mirror image that maps to a physical entity or system. This system can be updated in real-time to reflect the entire life cycle of the physical entity and support decision-making activities throughout the life cycle of the physical object.

In recent years, the main research directions have included: ① Intelligent data management and semantic modeling: Data is the foundation for the realization of digital twins. For the massive heterogeneous data collected by front-end sensors, research on data semantic modeling, cleaning, annotation, and organization is conducted, combining knowledge graphs and AI algorithms to realize semantic associations between data and physical mechanisms. ② Enhanced generative models with embedded physical mechanisms: Research on AI algorithms that integrate physical object operation mechanisms is conducted to generate data that conforms to real physical information to fill data gaps and enhance the generalization ability and simulation quality of the digital twin system. ③ Cross-modal, scale model fusion technology: Integrate multi-factor, multi-dimensional, multi-

domain mechanistic generation data and AI-generated data, fuse microscopic and macroscopic aspects of multi-level mechanistic models, and build complex system-level digital twin bodies to drive the evolution of digital twin bodies from “static description” to “dynamic analysis”. ④ Model correction technology: Continuously correct model parameters based on actual operational data, including real-time correction of data models and real-time correction of mechanistic models, to ensure the accuracy and iterative optimization of digital twin models.

From a broader perspective, the following aspects need further exploration: ① Autonomous intelligence: Digital twin bodies can proactively obtain valuable information from related twin nodes without notifying their physical entities through twin body interconnections to make intelligent decisions. ② Integration and coordination: Digital twin systems will evolve from single-domain implementation to multi-domain integration, deepening data integration depth, leveraging IoT platform cross-domain data integration capabilities to integrate data generated throughout the entire physical object life cycle. ③ Real-time and interactive: From the deployment model perspective, digital twin systems will combine local rendering and cloud rendering modes to meet different user needs and improve real-time interaction. ④ Security and privacy protection: As digital twin technology develops, data security and privacy issues need to be fully protected, especially when dealing with large amounts of sensitive data.

(9) Security testing and evaluation technology for artificial intelligence

The technology for security testing and assessment of AI focuses on comprehensive evaluation of the functionality, safety, robustness, and reliability of AI systems in complex application environments, ensuring their safe and controllable operation across various scenarios and tasks. This technology encompasses multidimensional assessment methodologies that span from the algorithmic level to the system level, primarily addressing potential vulnerabilities, attack surfaces, and risk points inherent to AI systems in complex environments. Through approaches such as testing, detection, simulation, and optimization, it aims to enhance the overall security of these systems. The technology for AI security testing and assessment has extensive application prospects in fields such as defense, finance, healthcare, autonomous driving, and industrial manufacturing.

Currently, the primary technological directions in this field include: ① Security vulnerability discovery and remediation: Leveraging static analysis, dynamic analysis, and symbolic execution methods to detect potential security flaws at the algorithmic and code levels, along with providing automated remediation suggestions. ② Robustness assessment: Using techniques such as adversarial sample generation, environmental disturbance simulation, and multimodal data augmentation to evaluate the sensitivity of AI systems to anomalous inputs or environmental changes. ③ Trustworthiness verification: Employing interpretable algorithms to analyze the decision-making process and behavioral logic of AI models, validating their reliability and consistency for critical tasks. ④ Dynamic risk monitoring: Establishing simulation environments and introducing real-time monitoring modules to capture any abnormal behaviors or deviations that may occur during the operation of AI systems.

Future development directions include: ① Multimodal fusion assessment technology: Constructing a cross-modal security assessment framework tailored for tasks involving voice, images, and text. ② Adversarial defense technology: Studying efficient detection and defensive methodologies to counter adversarial attacks, ensuring the robustness of AI systems under malicious conditions. ③ Standardized testing and tool development: Promoting the establishment of a unified AI security evaluation metric system and testing processes while developing efficient and automated testing assessment tools. ④ Complex scenario simulation and testing: Strengthening the ability to simulate and test the behaviors of intelligent agents in dynamic and uncertain environments to meet the diversity and complexity of future application demands.

As AI technology continues to be deeply applied and popularized, the security testing and assessment technologies will gradually form a standardized system, providing robust support for the trustworthy and controllable development of AI technologies.

(10) Integration technology of satellite, cloud, computing, and network

Integration technology of satellite, cloud, computing, and network leverages space-based cloud technology to form virtual units and infrastructure pool on satellites, integrating computing, transmission, and storage capabilities on board. This provides a unified infrastructure and enables data handling, storage, and service deployment on the satellites. The key technologies include:

① Multi-level cloud integration technology for network, computing, and storage. It achieves a unified abstraction and virtualization of multiple heterogeneous computing architectures within the satellite computing network. It masks the heterogeneity between space and ground networks at the infrastructure level and differences in space resources, ensuring dynamic and efficient storage of global data and real-time processing of massive computational power. ② Cross-layer collaborative orchestration and scheduling technology. Through collaborative evolution across the network layer, transport layer, and application layer, data and computing resources are dynamically routed, scheduled, and orchestrated based on user behavior and demands. It mitigates the topological dynamics caused by the high-speed relative motion between satellites and ground stations, ensuring efficient resource utilization in large-scale heterogeneous networks and providing reliable services for the satellite computing network. ③ Heterogeneous network dynamic organizing, control and management. Aimed at large-scale spatial-temporal coverage and ubiquitous access scenarios, the system shall support coordination for heterogeneous networks, variant service, and dynamic networking. It enables heterogeneous networks collaboration based on different service framework and protocols, to support mobility management, service continuity, as well as rapid networking and on-demand deployment in wide-area ubiquitous scenarios. ④ End-to-end service provisioning technology for heterogeneous networks. Research focuses on an end-to-end service framework for heterogeneous networks, covering multiple domains such as access networks, core networks, service planes, and management planes. It implements service quality assurance technologies like QoS, network slicing proposing efficient service management methods and mechanisms.

The development of low-Earth orbit (LEO) constellations and the diversification of real-time in-orbit services have heightened the demand for onboard computing power and coordination between space-based and ground-based computing networks. The future direction of nebula cloud-network convergence technology lies in enhancing efficiency, intelligence, and collaboration. This will overcome geographical limitations, improve service timeliness, achieve global and ubiquitous coverage and connectivity, and enable new types of anytime, anywhere services.

3.2.2 Interpretations for three key engineering development fronts

3.2.2.1 Integrated intelligent remote sensing monitoring technology for air-space-ground-sea

The development of integrated intelligent remote sensing monitoring technology for space-air-ground-sea has evolved from single-domain detection to multi-domain collaboration, from passive response to autonomous cognition, and from the observation of geophysical objects to human activity monitoring. Initially, remote sensing technology focused on developing sensors for larger-scale observations, primarily meeting basic geographic information needs. As monitoring tasks required higher precision and accuracy, remote sensing detection advanced towards a microscale, with spatial resolution improving from sub-meter to centimeter levels, temporal resolution enhancing from hourly to sub-second intervals, and spectral resolution expanding into hyperspectral ranges. This progression enabled comprehensive monitoring from broad area coverage to fine-grained feature capture.

However, relying solely on single-source detection methods to pursue higher accuracy cannot meet the growing demands of all-around monitoring tasks. Scientists have integrated aerial, spaceborne, ground-based, and maritime platforms, combining optical, synthetic aperture radar (SAR), ultrasonic, and other multimodal detection systems, thereby expanding the dimensions of information perception in remote sensing monitoring. Diverse mission requirements have also driven changes in the application models of remote sensing monitoring technology. The workflow of detection applications has shifted from a passive “task–requirement–detection–data” model to an autonomous “data–requirement–detection–data” approach. By integrating and analyzing historical and real-time monitoring data, this process optimizes various modes and temporal scales data into a “comprehensive spatial-temporal data map”, forming a dynamic switching mechanism between routine observation and triggered sensing, achieving integrated application of data products under multiple spatiotemporal coverages and detection dimensions.

Nonetheless, under the exponential explosion of multi-source data from optical, SAR, and hyperspectral sources, the

traditional remote sensing monitoring system characterized by “isolated efforts” across different domains and conventional information processing technologies struggle to systematically integrate fragmented detection resources or effectively distill high-value sparse information, significantly limiting application efficiency in complex scenarios. Combining AI technology, researchers have developed remote sensing spatiotemporal intelligence technology, transforming the traditional manual interpretation and supervised learning paradigm driven by data, establishing an interactive bridge for multi-domain remote sensing products across space-air-ground-sea, which greatly enhancing the application efficiency of remote sensing monitoring technology.

The main output countries and institutions of the core patents in the front of “integrated intelligent remote sensing monitoring technology for air-space-ground-sea” are listed in Tables 3.17 and 3.18, respectively. At the national level, China leads in the output of core patents but ranks only fifth in citations per patent. The USA and the Republic of Korea rank second and third in core patents, respectively, with the USA holding the second position in average citations, highlighting its technological quality and influence. Although Saudi Arabia, Israel, and Switzerland have fewer core patents, their citations per patent rank first, third, and fourth, respectively, indicating a higher quality of research. At the institutional level, State Grid Corporation of China produces the most patents. LG Electronics Inc. of the Republic of Korea, despite publishing only ten patents, boasts the highest citation per patent, demonstrating international competitiveness through high-quality patents. Figures 3.10 and 3.11 illustrate that cooperation between countries and institutions are relatively limited on a global scale, with the international cooperation network centered primarily around the USA, connecting countries like Israel and India. Institutional collaboration is concentrated mainly between China Electronics Technology Group Corporation and the Aerospace Information Research Institute of the Chinese Academy of Sciences.

As illustrated in Figure 3.12, the engineering development front of “integrated intelligent remote sensing monitoring technology for air-space-ground-sea” is poised to enter a critical phase over the next 5 to 10 years. This period will witness significant advancements driven by emerging multi-modal remote sensing detection systems that facilitate the construction of a ubiquitous data cube covering all domains. The goal is to achieve high-precision, multi-dimensional data acquisition and comprehensive digital and analytical representation of monitored environments.

Simultaneously, leveraging deep learning architectures based on sample-adaptive mining, this roadmap involves constructing generative large-scale remote sensing models to address challenges related to feature correlation and efficient integration of heterogeneous data. Additionally, dynamic digital twins will be developed to map environmental changes into virtual spaces, enabling real-time information sharing and interlinked application.

Table 3.17 Countries with the greatest output of core patents on “integrated intelligent remote sensing monitoring technology for air-space-ground-sea”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	817	85.55	3 317	81.60	4.06
2	USA	55	5.76	490	12.05	8.91
3	Republic of Korea	53	5.55	143	3.52	2.70
4	India	9	0.94	32	0.79	3.56
5	Australia	5	0.52	17	0.42	3.40
6	Israel	3	0.31	23	0.57	7.67
7	Switzerland	2	0.21	13	0.32	6.50
8	Russia	2	0.21	5	0.12	2.50
9	France	2	0.21	3	0.07	1.50
10	Saudi Arabia	1	0.10	10	0.25	10.00

Table 3.18 Institutions with the greatest output of core patents on “integrated intelligent remote sensing monitoring technology for air-space-ground-sea”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	State Grid Corporation of China	31	3.25	146	3.59	4.71
2	Baidu Inc.	15	1.57	61	1.50	4.07
3	Aerospace Information Research Institute, Chinese Academy of Sciences	14	1.47	56	1.38	4.00
4	China Electronics Technology Group Corporation	14	1.47	52	1.28	3.71
5	LG Electronics Inc.	10	1.05	91	2.24	9.10
6	Space Star Technology Co., Ltd.	10	1.05	49	1.21	4.90
7	Wuhan University	10	1.05	39	0.96	3.90
8	Beijing Institute of Technology	10	1.05	31	0.76	3.10
9	Guangdong Power Grid Co., Ltd.	9	0.94	24	0.59	2.67
10	Ping An Insurance (Group) Company of China	9	0.94	15	0.37	1.67

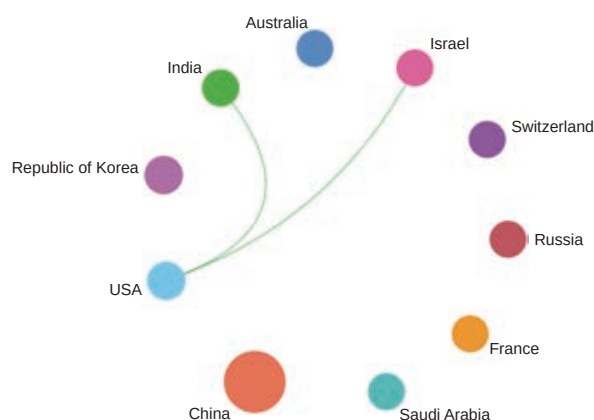


Figure 3.10 Collaboration network among major countries in the engineering development front of “integrated intelligent remote sensing monitoring technology for air-space-ground-sea”

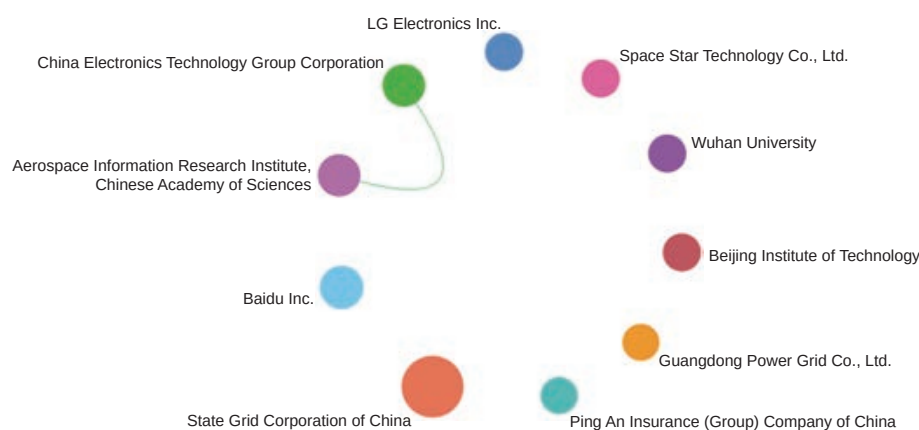


Figure 3.11 Collaboration network among major institutions in the engineering development front of “integrated intelligent remote sensing monitoring technology for air-space-ground-sea”

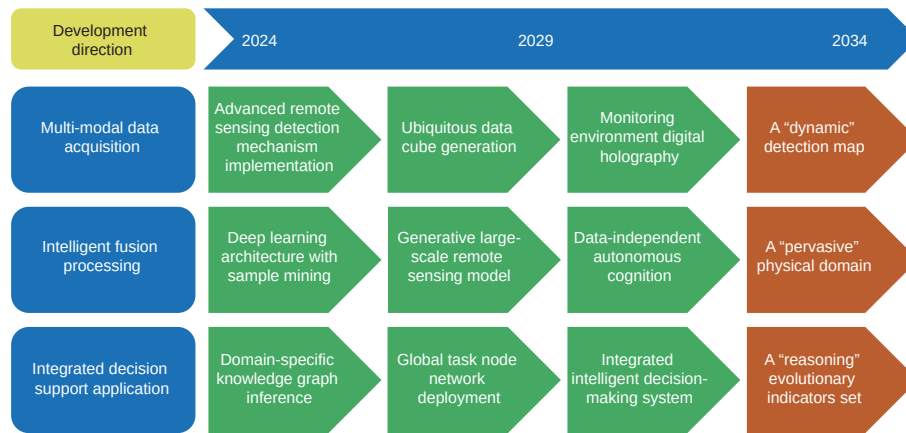


Figure 3.12 Roadmap of the engineering development front of “integrated intelligent remote sensing monitoring technology for air-space-ground-sea”

On this foundation, through domain-specific knowledge graph inference, the roadmap seeks to enhance capabilities for high-precision, autonomous, unsupervised decision-making. It also involves deploying task-oriented global node networks to provide technical support for intelligent decision-making in global resource scheduling. Ultimately, this will establish an integrated remote sensing monitoring system that unifies data acquisition, intelligent processing, and decision application into a unified system.

This transition shifts the paradigm from “event response under static data” to “intelligent scheduling under dynamic data”, paving the way for a new era of intelligent remote sensing monitoring that moves beyond data-centric approaches. These advancements will offer more efficient solutions and support platforms for areas such as environmental resource planning, modern urban governance, defense situational awareness, public safety assurance, and low-altitude economic development.

3.2.2.2 Wafer-level bonding technology for heterogeneous integration

Since the late 20th century, advancements in nanotechnology and microfabrication have spurred rapid development in heterogeneous integration wafer-level bonding technology. Japan’s Sony Corporation publicly reported on its back-illuminated CMOS image sensor (BI-CIS) IMX260 in 2016, which used Cu/SiO₂ hybrid bonding technology and was applied in Samsung’s Galaxy S7. Addressing the challenge of high-density integration for heterogeneous transistors/chips, USA Teledyne and others introduced a 250 nm InP HBT heterogeneously integrated with Si CMOS using wafer-level Cu/SiO₂ hybrid bonding technology in 2018, demonstrating a high-performance millimeter-wave integrated circuit. Taiwan Semiconductor Manufacturing Co., Ltd. launched its system-on-integrated-chips (SOIC) solution for 3D chip stacking, applied to platforms such as N7-on-N7 and N5-on-N5 as well as Logic-on-DTC, enhancing computational bandwidth and power optimization. During the same period, Wuhan XMC released a series of wafer-level heterogeneous integration platforms based on high-density hybrid bonding W2W and C2W, offering more options in sensors, memory, and computing power.

In recent years, as heterogeneous integration solutions from major process manufacturers have matured, companies like Intel, AMD, Apple, and NVIDIA have successively introduced heterogeneous integration product solutions that have received widespread market recognition. The technology has evolved from initial experimental explorations to commercial applications, transitioning from simple structures to complex systems and from inefficient manual operations to efficient automated production. Looking ahead, with the rise of emerging fields such as 5G, IoT, and AI, the demand for high-performance, multifunctional integrated chips will become more urgent, driving heterogeneous integration technology toward finer and more efficient development.

Currently, numerous research institutions and enterprises worldwide are engaged in the study and development of heterogeneous

integration technology. Leading universities and research institutions in the USA, Japan, Europe, such as the Massachusetts Institute of Technology, the University of Tokyo, and Germany's Fraunhofer Institutes, among others, are at the forefront of this field. Meanwhile, China has also increased its investment in R&D for this technology, with renowned enterprises and universities like Huawei and Tsinghua University actively positioning themselves in related research.

The main output countries of the core patents in the front of "wafer-level bonding technology for heterogeneous integration" is shown in Table 3.19. China leads in the output of core patents, accounting for approximately 60% of the total, although it ranks only 8th in citations per patent. The USA holds the second position with a share of 20.86%. Japan and the Republic of Korea also hold significant positions. The Netherlands, Belgium, and Israel have lower totals but excel in citations per patent, indicating high patent quality and technical value. Table 3.20 lists the leading institutions in patent output, where the Shanghai Institute of Microsystem and Information Technology of the Chinese Academy of Sciences, the China Electronics Technology Group Corporation, and Taiwan Semiconductor Manufacturing Co., Ltd. (TSMC) top the list. In terms of citations per patent, Monolithic 3D

Table 3.19 Countries with the greatest output of core patents on "wafer-level bonding technology for heterogeneous integration"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	334	59.54	942	46.13	2.82
2	USA	117	20.86	720	35.26	6.15
3	Japan	59	10.52	198	9.70	3.36
4	Republic of Korea	34	6.06	57	2.79	1.68
5	Singapore	5	0.89	33	1.62	6.60
6	Germany	4	0.71	15	0.73	3.75
7	Belgium	3	0.53	46	2.25	15.33
8	Israel	3	0.53	30	1.47	10.00
9	France	2	0.36	5	0.24	2.50
10	Netherlands	1	0.18	46	2.25	46.00

Table 3.20 Institutions with the greatest output of core patents on "wafer-level bonding technology for heterogeneous integration"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences	35	6.24	121	5.93	3.46
2	China Electronics Technology Group Corporation	35	6.24	101	4.95	2.89
3	Taiwan Semiconductor Manufacturing Co., Ltd.	32	5.70	306	14.99	9.56
4	International Business Machines Corporation	24	4.28	134	6.56	5.58
5	Intel Corporation	11	1.96	44	2.15	4.00
6	Monolithic 3D Inc.	10	1.78	128	6.27	12.80
7	Xidian University	10	1.78	38	1.86	3.80
8	Tongfu Microelectronics Co., Ltd.	10	1.78	15	0.73	1.50
9	Fujifilm Corporation	9	1.60	31	1.52	3.44
10	Institute of Microelectronics of Chinese Academy of Sciences	9	1.60	8	0.39	0.89

Inc. and TSMC lead significantly, with IBM ranking third.

Heterogeneous integration technology intersects multiple disciplines including materials science and micro-nano processing, serving as a critical key technology in chip manufacturing with significant implications for the development of information technology. Figure 3.13 illustrates that the USA, Japan, and France exhibit close cooperation, while the Netherlands and Belgium engage in exchanges. Other countries and regions need to enhance their external collaborations.

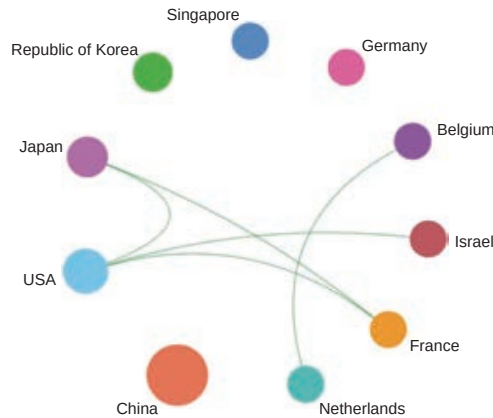


Figure 3.13 Collaboration network among major countries in the engineering development front of "wafer-level bonding technology for heterogeneous integration"

The key development directions for the next 5 to 10 years are as follows (Figure 3.14):

(1) Wafer-level 3D integration fundamental technologies and complete manufacturing lines

1) Vertical stacking integration technology: This includes high-density micro-sized through-silicon vias (TSV) and backside power delivery technologies, alongside nano-scale bonding pitch hybrid bonding techniques, especially chip-to-wafer bonding technology. By stacking chips with different functionalities and more layers in the vertical direction, higher integration and performance are achieved

2) Large-scale high-reliability production technology: It is aimed to enhance bonding accuracy and consistency to ensure high yield rates in large-scale production, and to develop efficient automated production lines to reduce manufacturing costs and increase productivity.

(2) Integrated design simulation and testing technologies

1) Joint design and simulation optimization technology for thermal, stress, electromagnetic, signal, voltage drop, ESD protection, and other aspects of heterogeneous integrated systems, which helps improve the design iteration cycle and reliability of the integration platform.

2) Development of EDA tools for design and simulation, such as achieving interoperability of design simulation files for multi-chip, cross-process, and different physical field designs, to support joint design simulation optimization (DTCO).

3) Preemptive test design for wafer-level systems, which conducts test designs for single-chip testing, post-integration testing, and package-end testing, and diagnoses related chip and 3D interconnection issues. Through rapid testing and screening, it is evaluated whether a tradeoff between system performance and cost is achieved.

(3) Development and application of new materials and equipment

1) Process new materials: To address the stress issues caused by the large differences in coefficients of thermal expansion among different dielectric materials in heterogeneous integration systems, interface materials with high bonding strength need to be

developed. Additionally, to cope with the thermal dissipation challenges brought by the increasing power density, new filling and interface materials with high thermal conductivity need to be developed.

2) Process new equipment. ① Key processing equipment: including new bonding equipment for achieving high-precision die-to-wafer (D2W) bonding, planarization equipment for high aspect ratio filling between dies with extremely high selectivity, edge processing equipment for wafers, and stress adjustment equipment. ② Inspection equipment: devices for analyzing warpage deformation and stress in heterogeneous integration, non-destructive 3D inspection techniques for high-aspect-ratio TSVs, rapid surface morphology detection, and modeling technologies to predict/optimize bonding process parameters.

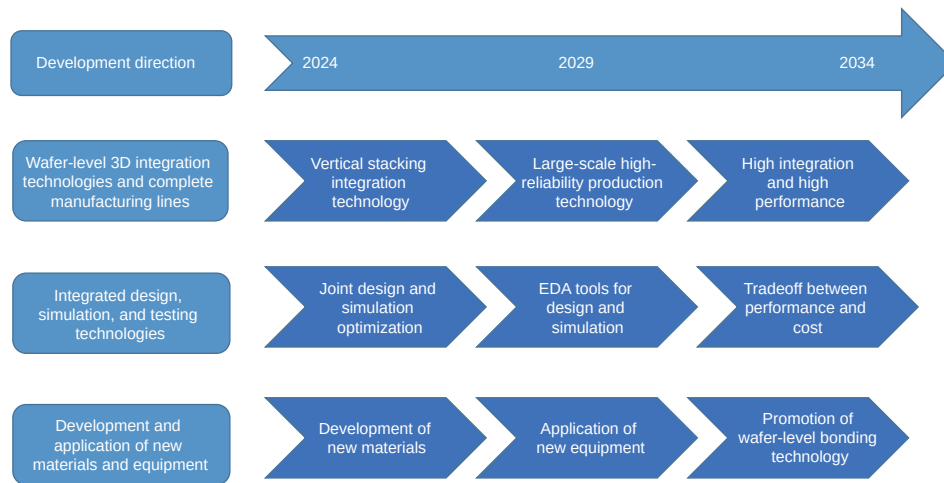


Figure 3.14 Roadmap of the engineering development front of “wafer-level bonding technology for heterogeneous integration”

Within the next 5 to 10 years, breakthroughs in these key development areas will position wafer-level bonding technology for heterogeneous integration to exhibit significant application potential in domains, such as high-performance computing, quantum information processing, biomedical devices, etc. Particularly in cutting-edge fields like quantum computers and neuromorphic computing, this technology is expected to become one of the core technologies driving rapid sector development. As maturity increases and costs decrease, its applications in consumer electronics will also expand, bringing greater convenience to daily life.

In summary, wafer-level bonding technology for heterogeneous integration will maintain a rapid development trend over the next 5 to 10 years. Through the application of new materials, breakthroughs in 3D integration technology, improvements in large-scale production techniques, and interdisciplinary convergence, it promises revolutionary changes in the field of information technology.

3.2.2.3 Intelligent computing technology based on large domain models

Intelligent computing technology based on large domain models takes specific professional fields as the entry point, combining general large models with domain-specific knowledge to address complex issues within these fields and drive industry advancement. Its core objective is to build specialized large models that provide intelligent, professional, and efficient computing solutions in areas such as healthcare, finance, law, government services, and scientific research. This technology builds upon the broad application of large models, undergoing deep optimization for vertical sector needs to achieve an organic combination of general knowledge and domain-specific expertise, thereby meeting diverse industry demands. The role of domain-specific large model intelligent computing technology in industrial intelligence and innovation is becoming increasingly significant.

The large-scale domain-specific model intelligent computing technology has demonstrated tremendous potential in driving digital transformation and intelligent innovation in various scenarios. ① In the financial advisory, BloombergGPT, a 50-billion-parameter financial language model released by Bloomberg, excels in financial tasks while maintaining competitiveness in

general scenarios. ② In the healthcare diagnosis, demonstrating substantial potential in digital transformation and intelligent innovation by providing high-quality answers to medical questions, exemplified by Google's Med-PaLM 2, which achieved expert-level performance on the USA Medical Licensing Examination (USMLE). ③ In the legal interpretation, SaulLM by Equall.ai and KL3M by Kelvin Legal leverage large models to effectively interpret and process legal texts, offering tailored AI solutions for legal professionals. ④ In the national defense and security sector, Defense Llama, developed by Scale AI in collaboration with the US military, adapts generative AI for special missions like combat planning and intelligence operations, aligning with military doctrine, international humanitarian law, and ethical principles.

In China, this field's research is primarily conducted by enterprises and universities. Internet companies such as Baidu have introduced the ERNIE bot series of large models covering various sectors including power, finance, aerospace, media, urban governance, film and television, energy, automotive, medical insurance, manufacturing, and humanities. Alibaba's Qwen series supports multiple vertical domains like healthcare and law. Huawei's Pangu series provides intelligent assistance in natural sciences, collaborating with the Shanghai Institute of Materia Medica at the Chinese Academy of Sciences to develop a drug molecule large model for AI-assisted drug design. In the education sector, platforms like Zhihu's ZhihuAI, NetEase Youdao's ZiYue, Kunlun Tech's TianGong, and TAL Education Group's MathGPT offer large models tailored for K-12 education.

The main output countries and institutions of the core patents in the front of "intelligent computing technology based on large domain models" are detailed in Tables 3.21 and 3.22. China leads in the output of core patents, accounting for approximately 55% of the total, followed by Japan with a share of 19.62%, and the USA with a share of 18.76%. Among the top ten institutions producing core patents, six are from China. Daichi Co., Ltd. ranks first, while Baidu Inc. and Tencent Technology (Shenzhen) Co., Ltd. rank second and third, respectively. Intel Corporation holds a mid-tier position in terms of patent publications but significantly surpasses other institutions in citations per patent.

As illustrated in Figure 3.15, from a national perspective, the USA has engaged in collaborations with many countries. Under the guidance of the USA, Canada, the Netherlands, and France exhibit particularly close cooperation among themselves. China, the UK, and Saudi Arabia primarily collaborate with the USA. This overview indicates that global collaboration between countries is still not sufficiently tight, necessitating further efforts in scientific research cooperation, technology exchange, and project collaboration to promote the development and application of this technology.

From an institutional standpoint, deep collaborations between major AI enterprises globally are relatively scarce. More frequently, collaborations occur between AI companies and vertical-sector firms, within multinational corporations, and along the upstream and downstream segments of the industry chain. There is an urgent need to establish a collaborative ecosystem for domain-specific large models on a global scale. By adopting open standards, data sharing, and joint projects, it will be possible to foster

Table 3.21 Countries with the greatest output of core patents on "intelligent computing technology based on large domain models"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	514	54.80	2 833	48.49	5.51
2	Japan	184	19.62	256	4.38	1.39
3	USA	176	18.76	2 175	37.22	12.36
4	Republic of Korea	16	1.71	48	0.82	3.00
5	UK	15	1.60	158	2.70	10.53
6	Netherlands	13	1.39	228	3.90	17.54
7	Canada	6	0.64	16	0.27	2.67
8	Germany	5	0.53	41	0.70	8.20
9	Saudi Arabia	3	0.32	35	0.60	11.67
10	France	3	0.32	34	0.58	11.33

Table 3.22 Institutions with the greatest output of core patents on “intelligent computing technology based on large domain models”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Daiichi Co., Ltd.	146	15.57	57	0.98	0.39
2	Baidu Inc.	77	8.21	354	6.06	4.60
3	Tencent Technology (Shenzhen) Co., Ltd.	47	5.01	548	9.38	11.66
4	Google Inc.	31	3.30	304	5.20	9.81
5	Huawei Technologies Co., Ltd.	16	1.71	70	1.20	4.38
6	Intel Corporation	13	1.39	329	5.63	25.31
7	Fujitsu Co., Ltd.	13	1.39	120	2.05	9.23
8	Netease (Hangzhou) Network Co., Ltd.	8	0.85	68	1.16	8.50
9	Beijing Zitiao Network Technology Co., Ltd.	8	0.85	55	0.94	6.88
10	Ping An Insurance (Group) Company of China	8	0.85	27	0.46	3.38

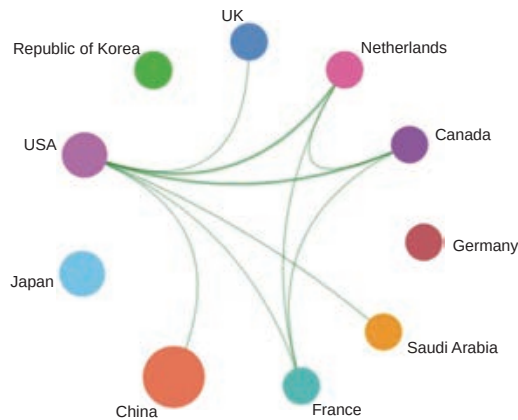


Figure 3.15 Collaboration network among major countries in the engineering development front of “intelligent computing technology based on large domain models”

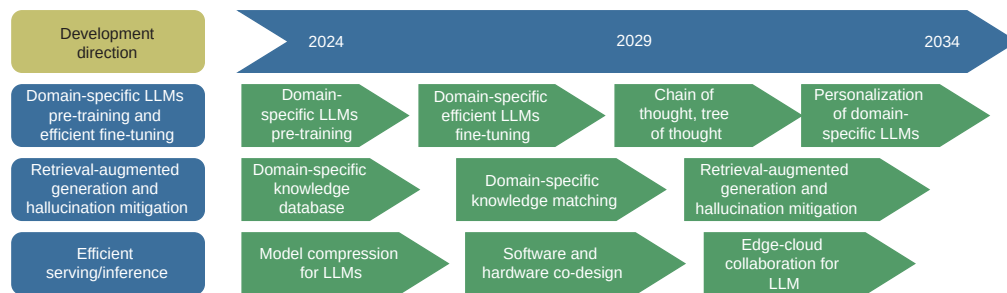


Figure 3.16 Roadmap of the engineering development front of “intelligent computing technology based on large domain models”

synergistic cooperation among all parties, thereby advancing the technology further.

As illustrated in Figure 3.16, the front of “intelligent computing technology based on large domain models” will focus on the following three key development directions over the next 5 to 10 years:

1) Domain-specific LLMs pre-training and efficient fine-tuning techniques. In the future, domain-specific large models will place greater emphasis on pre-training with domain data and efficient fine-tuning techniques. During the pre-training phase, there will be an optimization of large-scale data collection and cleaning processes tailored to vertical sectors, combined with data augmentation and generation technologies to produce high-quality domain-specific corpora. In the fine-tuning phase, the focus will be on developing methods such as domain instruction optimization, chain-of-thought and reasoning tree prompting, parameter-efficient, and memory-efficient fine-tuning approaches. These methods will enable rapid adaptation of the model to specific tasks using small, highly accurate labeled datasets. This direction will drive the efficient deployment of personalized models and enhance the model’s understanding and generation capabilities in vertical domains.

2) Retrieval-augmented generation and hallucination mitigation techniques. Retrieval-augmented generation technology will become one of the core technologies for vertical domain models in the future. This direction will integrate symbolic knowledge bases with neural networks to develop efficient retrieval and interaction modules. By incorporating dynamic updates and semantic matching optimization techniques, domain models can obtain up-to-date and reliable domain information in real-time. Hallucination mitigation techniques will focus on leveraging retrieval augmentation and designing feedback mechanisms to correct erroneous content generated by large domain models in real-time. This not only enhances the reliability of the generated content but also improves the model’s ability to answer complex questions, thereby boosting its applicability in knowledge-intensive industries like medicine and law.

3) Efficient serving/inference. Large models face challenges such as high computational power consumption and costly deployment, which hinder their application in resource-constrained devices and large-scale applications. Lightweighting of large models is critical for broadening their application in domain-specific scenarios. Future lightweighting technologies for domain-specific large models will concentrate on deep integration of sparsification, quantization, low-rank approximation algorithms to achieve highly sparse and precise edge-side inference models. Efforts will also advance software–hardware co-optimization design, exploring hardware design sensitive to lightweight algorithms to realize a collaborative inference system for edge-side processing. Additionally, cloud-edge collaboration will be promoted to facilitate the pervasive deployment of large models, expanding their application potential comprehensively and shaping a new ecosystem for intelligent technologies.

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Chapter 4 Chemical, Metallurgical, and Materials Engineering Fronts



4.1 Engineering research fronts

4.1.1 Trends in the Top 10 engineering research fronts

The Top 10 engineering research fronts, as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering, are shown in Tables 4.1 and 4.2. “Ultra-thin and ultra-wideband high-performance electromagnetic wave-absorbing materials” was obtained according to core-paper statistics provided by Clarivate Analytics, with 266.54 citations per paper. “Purification and separation of similar elements in metallurgical processes” and “reaction mechanisms and theories of unconventional resource smelting processes” in the metallurgical field were directly recommended by experts, but the citations are not high. “Design and discovery of novel smart materials based on machine learning” and “catalytic degradation of polyolefin and polyester into valuable chemicals” were also recommended by experts. From the mean year in 2020 (Table 4.1) and the increasing annual number of core papers for these two topics (Table 4.2), they have received more attention from researchers. The other fronts were chosen by a panel of experts using core-paper statistics provided by Clarivate Analytics. Hydrogen energy (including hydrogen storage and solar photocatalytic hydrogen production) and lithium batteries remain hot topics.

(1) Controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials

Solid-state hydrogen storage is a hydrogen storage method involving the interaction between solid-state materials and hydrogen. Solid-state materials, such as metal hydrides and complex hydride materials, are of particular interest because they are capable of absorbing hydrogen in the bulk phase through chemical bonding. They have several advantages, including high hydrogen storage density, high safety, and high hydrogen purity, making them a focus of research in high-capacity solid-state hydrogen

Table 4.1 Top 10 engineering research fronts in the chemical, metallurgical, and materials engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials	276	36 900	133.70	2019.9
2	Design and discovery of novel smart materials based on machine learning	96	10 327	107.57	2020.5
3	Purification and separation of similar elements in metallurgical processes	148	7 592	51.30	2019.5
4	Electrode material design and the reaction mechanism of ultra-low temperature Li-ion batteries	77	10 712	139.12	2019.4
5	Highly biomimetic brain-like neuron materials and devices	103	18 080	175.53	2019.7
6	Ultra-thin and ultra-wideband high-performance electromagnetic wave-absorbing materials	99	26 387	266.54	2018.5
7	Key chemical issues in photo(electro)catalytic water splitting for hydrogen production	151	39 941	264.51	2019.3
8	Bioprobe materials based on precision medicine	146	17 799	121.91	2019.5
9	Catalytic degradation of polyolefin and polyester into valuable chemicals	170	20 902	122.95	2020.1
10	Reaction mechanisms and theories of unconventional resource smelting processes	167	16 852	100.91	2019.7

Table 4.2 Annual number of core papers published for each of the Top 10 engineering research fronts in the chemical, metallurgical, and materials engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials	51	69	64	55	33	4
2	Design and discovery of novel smart materials based on machine learning	11	10	28	19	24	4
3	Purification and separation of similar elements in metallurgical processes	44	39	34	17	9	5
4	Electrode material design and the reaction mechanism of ultra-low temperature Li-ion batteries	22	26	13	12	4	0
5	Highly biomimetic brain-like neuron materials and devices	20	24	28	24	7	0
6	Ultra-thin and ultra-wideband high-performance electromagnetic wave-absorbing materials	13	18	12	18	6	1
7	Key chemical issues in photo(electro)catalytic water splitting for hydrogen production	52	37	33	22	7	0
8	Bioprobe materials based on precision medicine	48	32	32	23	8	3
9	Catalytic degradation of polyolefin and polyester into valuable chemicals	27	36	37	42	24	4
10	Reaction mechanisms and theories of unconventional resource smelting processes	38	38	46	34	10	1

storage materials. Nevertheless, elevated thermodynamic and kinetic energy barriers constrain the practical deployment of high-capacity solid-state hydrogen storage materials. It is essential to controllably tune the thermodynamic and kinetic properties by inserting other substances, adding catalysts, or altering the morphology to control the operating temperature, pressure, and other performance parameters of the hydrogen storage materials, thus making them suitable for application. The primary research avenues are currently focused on the following areas: ① The coupling of multiple hydrogen-containing compounds is expected to alter the hydrogen absorption/desorption reaction pathway of solid-state hydrogen storage materials, thereby modulating the thermodynamic energy barrier. ② The design of high-performance catalysts for different solid-state hydrogen storage systems is intended to reduce the kinetic energy barrier. ③ Modification of the preparation method effectively alters the microstructure and particle size of solid-state hydrogen storage materials, as well as the dynamic energy barrier. ④ The introduction of external fields, such as light and microwaves, allows for modulation of the morphology, thermal distribution, reaction pathways, and other factors, thereby influencing the hydrogen storage performance of the materials.

(2) Design and discovery of novel smart materials based on machine learning

Smart materials are capable of responding to external environmental stimuli, such as temperature, humidity, light, magnetic fields, and electric fields, thus adapting to various application conditions. These materials have significant value in aerospace, architecture, medical devices, sensors, mobile devices, and flexible electronics. The design of novel smart materials based on machine learning represents an innovative interdisciplinary research field, where the powerful data feature extraction capabilities of machine learning are leveraged to investigate and discover materials. By establishing complex relational models between multiple factors, like material composition, structure, and fabrication processes, and their performance, it becomes possible to rapidly and accurately predict and design new smart materials that meet specific performance requirements. This greatly enhances the efficiency and success rate of material development. The main research focuses are summarized as follows: ① Study of the response mechanisms in smart materials: an in-depth exploration of how external stimuli affect materials, providing a theoretical foundation for material design. ② Construction of rich and accurate material databases: accelerating the discovery of new materials through multiscale simulations coupled with high-throughput experimental techniques, leading to the creation of databases encompassing numerous material structures, properties, and synthesis conditions. ③ Algorithm development and material screening: developing machine learning algorithms suited for smart

material design, aimed at clarifying the structure-property relationships in materials. This also includes the screening of novel smart materials that meet physical property requirements and achieving reverse material design. Data-driven machine learning technology is providing a new paradigm for smart material design and development. Future efforts should focus on further improving model interpretability, ensuring the consistency of quantitative descriptions of material properties, and enhancing the transferability of functional design.

(3) Purification and separation of similar elements in metallurgical processes

The efficient purification and separation of similar elements is key to improving the quality of metallurgical products. With the rapid development of strategic emerging industries, such as new energy and information storage, the demand for high-end metal materials is increasing. The preparation of high-end metal materials not only requires precision equipment and instruments but also relies on the availability of high-purity metal raw materials. The preparation of high-purity metal raw materials requires the highly efficient and specific purification and separation of impurities in the metallurgical process, especially during the separation of similar elements. Research efforts mainly focus on: ① developing new theories for the highly selective separation of similar elements and process regulations, identifying mechanisms of host-guest interactions and potential targets; ② establishing new multiscale separation methods for similar elements in co-associated systems; ③ developing in situ characterization techniques for analyzing the dynamics of separation processes; ④ designing extractants based on machine learning and molecular dynamics simulations; ⑤ revealing migration rules for impurity elements in the separation of similar elements, and establishing new methods and standards for the quantitative analysis of trace impurities.

(4) Electrode material design and the reaction mechanism of ultra-low temperature Li-ion batteries

Lithium-ion batteries occupy a huge market share in the field of power storage owing to their high energy density and long service life. However, the suitable working temperature of commercial lithium-ion batteries is 10–35 °C, which makes it difficult to operate under low-temperature conditions, not to mention working in extremely low-temperature environments such as the deep sea and space. Therefore, the development of high-specific energy ultra-low temperature lithium-ion batteries has great practical application value. Research on low-temperature batteries started around the end of the 20th century, and the key technologies include four main aspects: ① Preparation of electrode materials: developing electrode materials with high ion/electronic conductivity and improving the surface properties of electrode materials by leveraging surface coating technology and interface engineering. ② Low-temperature electrolyte development: reducing the freezing point of the electrolyte toward improved ion conductivity at low temperatures. ③ Battery structure optimization: optimizing the packaging structure of the battery and improving its sealing and insulation for low-temperature operation. In addition, the charge transfer rate and energy density of the battery at low temperatures can be improved by optimizing the electrode structure and electrolyte circulation. ④ Thermal management system design: employing a heat management system that can heat the battery during the charge and discharge process and enhance its electrochemical reaction kinetics under low temperatures.

(5) Highly biomimetic brain-like neuron materials and devices

Highly biomimetic brain-like neuronal materials and devices are designed to mimic biological neurons and perform parallel information processing functions such as learning, memory, encoding, and processing, showing great promise for applications in military operations, disaster relief, health monitoring, robotics, man-machine interfaces, and artificial intelligence. Research is generally focused on the following aspects: ① Development of highly biomimetic intelligent materials: exploring new materials that effectively simulate neuron and synapse behavior using ion cascade reactions and selective regulation. The goal is to develop materials with multi-ion interactions and understand ion migration mechanisms to achieve more complex biological neuronal functions. ② Simulation of biological neuronal functions: analyzing and replicating advanced intelligent behaviors and functions of biological systems. Efforts may be directed toward developing synaptic, neuronal, and neural network functions with high-order complexity to enable sophisticated signal processing and analysis. ③ System integration of neuromorphic devices: enhancing interconnection integration and ensuring stable and efficient signal transmission at the hardware level. This refers to developing devices characterized by real-time responsiveness and stable operational lifetimes. ④ Application demonstration: improving

system performance consistency, as well as the stability of perception, understanding, and decision-making functions. This may support the practical application of highly biomimetic brain-like materials and devices in intelligent robots, brain-computer interfaces, and smart medical applications.

(6) Ultra-thin and ultra-wideband high-performance electromagnetic wave-absorbing materials

Ultra-thin and ultra-wideband high-performance electromagnetic wave-absorbing materials have a thin physical form and provide efficient wideband absorption in multi-band electromagnetic environments. As electromagnetic interference problems become increasingly prominent in 5G communications, smart transportation, aerospace, and national defense equipment, there is an urgent need to develop thin and lightweight materials with high absorption efficiency and wide bandwidth. From the perspective of material microstructure, interface characteristics and overall preparation level, the current research direction is mainly focused on: ① high-throughput characterization and the correlation of material micromagnetolectric structure and material dispersion characteristics; ② refined control of interfacial properties in the material composite molding process; ③ electromagnetic evolution rules, performance degradation mechanisms, and control technologies of corresponding materials under complex and changeable service environments; ④ large-scale preparation, optimization, and control of ultra-thin and ultra-light absorbing materials.

(7) Key chemical issues in photo(electro)catalytic water splitting for hydrogen production

Solar fuels, which have attracted worldwide attention, rely on solar photocatalytic and photoelectrochemical processes (i.e., converting water and carbon dioxide into value-added fuels and chemicals using solar energy). Solar photocatalytic and photoelectrochemical processes involve multi-electron transfer pathways spanning multiple timescales, from femtoseconds to seconds. Furthermore, these systems involve atomic-scale structures, space charge layers, and charge diffusion distances ranging from hundreds of nanometers to tens of micrometers. The major physicochemical issues that require attention include: ① the separation, transport, and spatial distribution of photogenerated charges in photocatalyst systems; ② high-sensitivity and spatiotemporally resolved characterization techniques for photogenerated charges; ③ biomimetic catalysts that mimic natural photosynthesis processes; ④ microscopic mechanisms of water oxidation reaction in water splitting; ⑤ chemical bonding dynamics during water splitting at the molecular level.

(8) Bioprobe materials based on precision medicine

Bioprobe materials based on precision medicine are multifunctional biomedical materials that integrate diagnostic and therapeutic capabilities. These materials are designed to selectively interact with specific biological targets or molecules associated with diseases in vitro or in vivo, enabling the early diagnosis and treatment of specific diseases. Current research efforts are mainly focused on: ① developing highly sensitive in vitro diagnostic bioprobe materials for early detection, accurate staging, and pathological classification of major diseases by detecting biomarkers at trace levels; ② developing multi-physical field responsive bioprobe materials to achieve real-time visualization and theranostics of major diseases; ③ establishing highly specific and adaptable bioprobe materials to offer new strategies for the personalized diagnosis and treatment of diseases. In the future, bioprobe materials may be further integrated with proteomics, metabolomics, and genomics to investigate their molecular mechanisms. Simultaneously, standardization is necessary to expedite the clinical translation and application of bioprobe materials based on precision medicine.

(9) Catalytic degradation of polyolefin and polyester into valuable chemicals

Catalytic degradation strategies are being developed to convert plastic waste into high-value chemicals, considering that the transformation of waste into valuable products is an effective way to achieve sustainable development. In the catalytic degradation of polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyester (PET) and other long-life polymers to high-value chemicals, efficient and stable catalysts are required to selectively break C—C and C—O bonds, directionally cutting the polymers and generating small molecules. For different polymer systems, different strategies are being adopted. ① PE and PP can be converted into oils using metal oxide and molecular sieve catalytic systems, and with existing petroleum refining systems,

these oils can be used to produce gasoline and diesel. CO_2 can also be introduced into the aromatization process of waste plastics, neutralizing the excess hydrogen in PE and PP, which not only reduces the reaction temperature and achieves efficient preparation of aromatic hydrocarbons but also consumes approximately 0.2 tons of CO_2 per ton of converted waste plastic. ② PS can be transformed into monocyclic aromatic hydrocarbons, such as ethylbenzene by employing catalytic hydrogenation. Furthermore, oxidation via thermal catalysis and photocatalysis degrades PS into benzoic acid and other chemicals. ③ Through the action of metal and acid-base bifunctional catalysts, the degradation of PET via hydrolysis, alcoholysis, hydrogenolysis, and ammonolysis can produce the corresponding polymeric monomer or related derivatives.

(10) Reaction mechanisms and theories of unconventional resource smelting processes

With the depletion of traditional high-quality mineral resources, unconventional resources, such as urban minerals, industrial waste residues, and hazardous waste, are becoming important raw materials for metal production. Unlike natural minerals, the coexistence of polymetallic components in urban minerals and industrial solid waste, as well as the complex relationships between their material structures and phases, leads to high recovery costs, large metal losses, and significant secondary pollution. Low-carbon, clean recycling of unconventional secondary resources is of great significance in breaking the resource and environmental bottleneck in the metallurgical industry. Therefore, it is urgent to improve the basic theoretical system of metallurgical processes for unconventional metal resources. The main research directions focus on: ① reaction mechanisms in the smelting process of multi-source complex raw material components, revealing the migration and distribution rules of polymetals and the principles of directional regulation; ② reaction mechanisms and regulation principles of polymetals and slag-forming agents in unconventional raw materials, developing efficient selection, enrichment, separation, and extraction methods; ③ formation, migration, and transformation of smelting flue gases in unconventional resources, developing source suppression methods for gaseous pollutants such as polymer gases and dioxins; ④ optimization of existing multi-phase and multi-field coupling theories and numerical simulations for smelting processes, developing smelting technology and equipment focused on unconventional resources composed of non-ferrous metals and steel.

4.1.2 Interpretations for three key engineering research fronts

4.1.2.1 Controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials

In the context of addressing climate change, the global energy strategies and supply-demand patterns are undergoing a period of significant adjustment and transformation. The International Energy Agency has forecasted that the use of hydrogen and hydrogen-based fuels will reach 500 million tons per year by 2050. Similarly, the International Hydrogen Council has predicted that hydrogen will account for 22% of carbon emissions reduction by 2050. As indicated in the International Research Report on Hydrogen Energy Technology and Industry Development 2023, approximately 680 green hydrogen projects have been announced globally, with a planned cumulative installed capacity of hydrogen electrolysis cells exceeding 460 GW. Hydrogen storage technology represents a pivotal link in the hydrogen energy supply chain, attracting considerable attention. Solid-state hydrogen storage materials offer several advantages, including high-quality and high-volume hydrogen storage density, abundant raw material sources, and low costs. As a result, they represent one of the most promising areas of research in the field of hydrogen storage. Nevertheless, the hydrogen absorption/desorption processes have high thermodynamic/kinetic energy barriers, which require high temperatures to overcome and limit the energy efficiency of solid-state hydrogen storage materials.

Tuning the thermodynamic performance of solid-state hydrogen storage materials necessitates the introduction of additional substances to modify their hydrogen release reaction pathway, thereby reducing the overall enthalpy change of the hydrogen absorption/desorption process. Concurrently, the introduction of additional substances results in a corresponding alteration in hydrogen storage density. Modulating the kinetic performance necessitates the incorporation of catalysts that assist dissociation and recombination of hydrogen. Ti-based catalysts, for instance, exhibit high catalytic efficiency across a range of solid-state

hydrogen storage materials. However, the introduction of catalysts typically causes a reduction in hydrogen storage capacity. Therefore, the development of lightweight and efficient catalysts for different hydrogen storage systems is a crucial objective. Furthermore, the morphology of the materials influences their hydrogen storage performance. The particle size affects the migration distance of hydrogen during diffusion, and the morphology is related to the number of surface-active sites, which affects the nucleation and growth process of hydrides during hydrogen absorption. Moreover, external-field effects have gained great attention in recent years. These effects can be implemented at various stages to alter the materials and enhance their hydrogen storage performance. During the preparation stage, external fields can significantly alter the morphology, particle size, and other morphological characteristics. In the hydrogen absorption/release stage, an external field can be employed as an indirect driving force to promote hydrogen absorption/desorption. For example, light or microwaves can be used to heat MgH_2 and facilitate the release of hydrogen by locally generating high temperatures, which significantly reduces the macroscopic hydrogen release temperature of the hydrogen storage system and lowers the energy consumption associated with hydrogen release. Some semiconductor hydrides display photocatalytic activity, whereby they absorb photons and undergo self-decomposition.

Researchers from numerous countries are actively investigating various solutions for hydrogen storage in laboratory and industry. Tables 4.3 and 4.4 illustrate the countries and institutions that have published most of the core papers related to the “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”. Notably, 61.59% of the core papers are from China, with the Chinese Academy of Sciences and Zhejiang University producing most of the publications. The USA, Australia, Germany, and Japan account for 5%–15% of the total output. Figures 4.1 and 4.2 illustrate the collaborative networks between major countries and institutions. The graphics demonstrate that scientists around the globe are engaged in extensive cooperation in this field, with China and the USA demonstrating the highest levels of collaboration. Tables 4.5 and 4.6 show that China accounts for 58.12% of the total output among countries producing core papers. Additionally, the top ten institutions producing the most core papers are Chinese universities or research institutes, including Chinese Academy of Sciences, University of Science and Technology of China, Zhengzhou University, and Zhejiang University. In particular, the Chinese Academy of Sciences accounts for 28.28% of the citing papers.

To meet the urgent demand for clean energy systems worldwide, it is necessary to accelerate the research and development in the following areas: performance regulation, efficient synthesis, large-scale production, and demonstrable applications of solid hydrogen storage materials. Furthermore, a high-density, lightweight, low-cost, and diversified hydrogen energy storage and transportation system must be constructed. Finally, the transition from hydrogen energy preparation to application must be achieved through scaling up and cost reduction (Figure 4.3).

Table 4.3 Countries with the greatest output of core papers on “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	170	61.59	22 984	135.20	2019.9
2	USA	37	13.41	4 296	116.11	2019.5
3	Australia	30	10.87	4 195	139.83	2020.0
4	Germany	20	7.25	3 510	175.50	2019.8
5	Japan	18	6.52	3 836	213.11	2019.8
6	UK	13	4.71	2 580	198.46	2020.0
7	Republic of Korea	11	3.99	1 312	119.27	2020.0
8	Canada	10	3.62	1 121	112.10	2020.8
9	France	9	3.26	1 695	188.33	2019.1
10	India	9	3.26	759	84.33	2020.0

Table 4.4 Institutions with the greatest output of core papers on “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Zhejiang University	14	5.07	1 306	93.29	2019.3
2	Chinese Academy of Sciences	13	4.71	2 714	208.77	2019.8
3	South China University of Technology	12	4.35	1 708	142.33	2020.1
4	Nankai University	11	3.99	2 273	206.64	2019.6
5	Shanghai University	8	2.90	1 640	205.00	2020.5
6	Institute for Energy Technology Norway	8	2.90	1 488	186.00	2019.6
7	University of Macau	8	2.90	1 305	163.12	2019.1
8	Kyushu University	8	2.90	1 180	147.50	2019.8
9	Shanghai Jiao Tong University	8	2.90	901	112.62	2020.9
10	Nanjing Tech University	8	2.90	579	72.38	2020.2

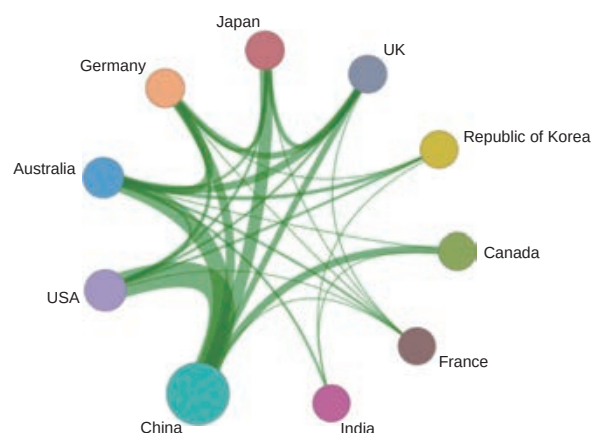


Figure 4.1 Collaboration network among major countries in the engineering research front of “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

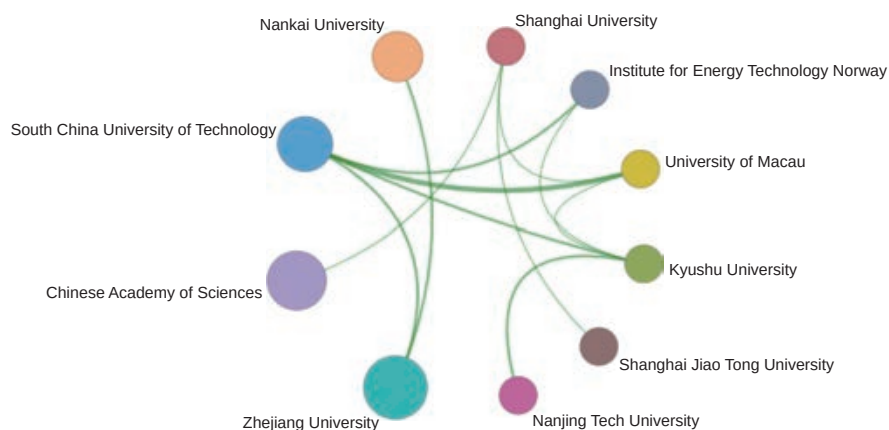


Figure 4.2 Collaboration network among major institutions in the engineering research front of “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

Table 4.5 Countries with the greatest output of citing papers on “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	16 713	58.12	2022.0
2	USA	2 212	7.69	2021.7
3	India	1 898	6.60	2022.2
4	Republic of Korea	1 711	5.95	2022.1
5	Australia	1 160	4.03	2021.8
6	Germany	1 064	3.70	2021.8
7	Japan	988	3.44	2021.8
8	UK	934	3.25	2022.0
9	Saudi Arabia	882	3.07	2022.4
10	Iran	616	2.14	2021.9

Table 4.6 Institutions with the greatest output of citing papers on “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	1 665	28.28	2021.9
2	University of Science and Technology of China	491	8.34	2021.9
3	Zhengzhou University	487	8.27	2021.8
4	Zhejiang University	486	8.25	2021.9
5	Tsinghua University	442	7.51	2022.1
6	Tianjin University	431	7.32	2021.9
7	Harbin Institute of Technology	417	7.08	2022.0
8	Xi'an Jiaotong University	381	6.47	2022.2
9	Central South University	379	6.44	2022.0
10	Shanghai Jiao Tong University	361	6.13	2022.1

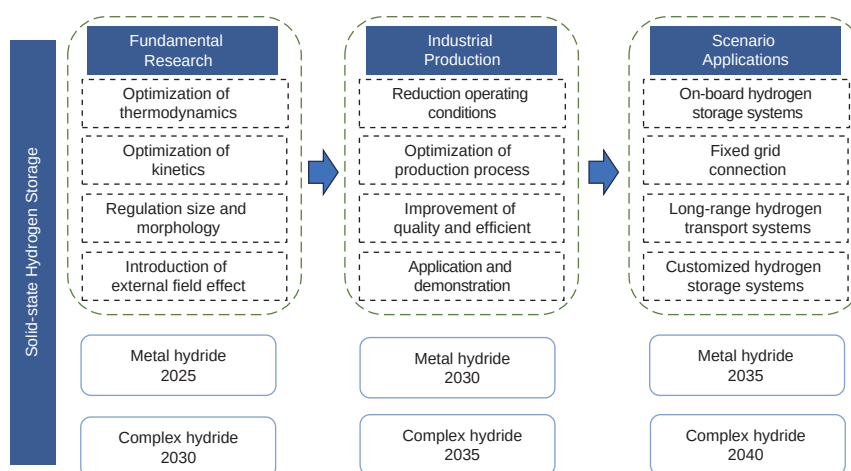


Figure 4.3 Roadmap of the engineering research front of “controllable modulation of thermodynamic and kinetic properties in high-capacity solid-state hydrogen storage materials”

4.1.2.2 Design and discovery of novel smart materials based on machine learning

Smart materials are capable of responding to stimuli in the environment by subsequently altering their properties or structures, thus exhibiting characteristics of self-adaptation, self-repair, and self-diagnosis. Therefore, these materials are increasingly becoming a focus in the field of materials science. The concept of smart materials originated in the mid-20th century, with the development of shape-memory alloys that respond to various external stimuli, particularly temperature changes. With advancements in manufacturing and nanotechnology, smart materials have rapidly evolved and found practical applications in adaptive wing materials, adaptive displays, minimally invasive surgical instruments, self-healing fabrics, switches, and smart sensors. Currently, the design of novel smart materials follows several development trends: ① High strength and efficient response: enhancing the materials' ability to rapidly and precisely respond to one or multiple environmental changes, enabling more types of intelligent behaviors for adaptation in more complex application scenarios. ② Multifunctional integration: integrating multiple response characteristics into a single material, endowing it with several functions such as sensing, regulation, and actuation. ③ Biomimetic design: mimicking natural biological functions to develop materials with self-repair and protective features. ④ Green and sustainable: improving the degradability and biocompatibility of materials while enhancing environmental awareness in material design.

As the demand for the diversity, flexibility, and complexity of smart material applications increases, higher requirements are placed on material design methods. Machine learning provides the ability to process complex nonlinear data and enables a paradigm shift in the design and development of smart materials. By leveraging high-throughput material screening, property prediction, and reverse design, driven by vast amounts of data, machine learning is expected to accelerate the design, selection, and optimization of novel smart materials. These studies cover the entire process from molecular design and structural simulation to performance testing. Future research on the design of novel smart materials based on machine learning may focus on the following areas: ① Intrinsic mechanisms of material perception and response: conducting in-depth research on the interaction mechanisms between materials and various stimuli to identify material structures and compositions that can effectively convert external stimuli into detectable signals. This involves studying response mechanisms based on various physical and chemical changes to precisely control parameters like response temperature, response time, and response intensity. ② Model algorithm development and multiscale simulation optimization: further optimizing machine learning algorithms by combining deep data mining and optimization to improve prediction accuracy and generalization capabilities. This involves developing models better suited for complex material systems, considering the micro, meso, and macro structures of materials, and combining multiscale simulation techniques to build pathways for multiscale structure and performance analysis and optimization. The goal is to achieve comprehensive prediction and validation of smart materials and improve the reliability of the design. ③ Data-driven collaborative design innovation of smart materials: fully utilizing big data and cloud computing technologies to build material databases and knowledge graphs, fulfilling the interconnected requirements of smart materials across various performance dimensions. This allows for the design of materials with superior overall performance and enables personalized design and precise matching of specific performance indicators based on different application conditions and requirements.

In recent years, China has produced 39.58% of the core papers related to the “design and discovery of novel smart materials based on machine learning”, ranking first globally, followed by the USA and the UK (Table 4.7). China and the USA each contain four of the top ten major output institutions, with the Chinese Academy of Sciences and Tsinghua University ranking first and second, respectively (Table 4.8). The collaboration networks between major countries and institutions show extensive global cooperation and exchange, with regional collaboration trends between China and the USA, and between the USA and Europe (Figures 4.4 and 4.5). As shown in Tables 4.9 and 4.10, China ranks first in the number of highly citing papers, with 4 424, accounting for 43.34% of the total. Seven of the top ten institutions producing these highly citing papers are from China, reflecting their close attentions to this field.

The research of new smart material design based on machine learning has developed rapidly in recent years. Constructing a data-driven paradigm for exploring the intrinsic mechanism of material perception and designing new smart materials is a key issue for the further development. As shown in Figure 4.6, future research should focus on the response mechanism of smart materials, revealing the effective transformation relationship of material structure and composition to external stimuli. Meanwhile, machine learning will be used to mine the multi-dimensional characteristic information of materials, and then the basic framework of a smart material knowledge graph is constructed. The formation of a rich and accurate database is an important guarantee for

Table 4.7 Countries with the greatest output of core papers on “design and discovery of novel smart materials based on machine learning”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	38	39.58	3 585	94.34	2020.8
2	USA	33	34.38	4 067	123.24	2020.4
3	UK	13	13.54	1 556	119.69	2020.9
4	Australia	9	9.38	869	96.56	2021.6
5	Germany	7	7.29	1 207	172.43	2021.3
6	Republic of Korea	7	7.29	978	139.71	2019.6
7	Spain	6	6.25	623	103.83	2020.0
8	Singapore	5	5.21	495	99.00	2021.0
9	India	5	5.21	454	90.80	2020.0
10	France	4	4.17	529	132.25	2021.5

Table 4.8 Institutions with the greatest output of core papers on “design and discovery of novel smart materials based on machine learning”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	8	8.33	964	120.50	2020.8
2	Tsinghua University	6	6.25	522	87.00	2020.7
3	Georgia Institute of Technology	5	5.21	522	104.40	2021.4
4	Guangxi University	4	4.17	496	124.00	2021.0
5	Beihang University	4	4.17	337	84.25	2020.8
6	Nanyang Technological University	3	3.12	276	92.00	2020.7
7	Friedrich Alexander University Erlangen Nurnberg	2	2.08	575	287.50	2020.0
8	Harvard University	2	2.08	546	273.00	2018.5
9	University of California, Berkeley	2	2.08	533	266.50	2018.5
10	Seoul National University	2	2.08	524	262.00	2019.0

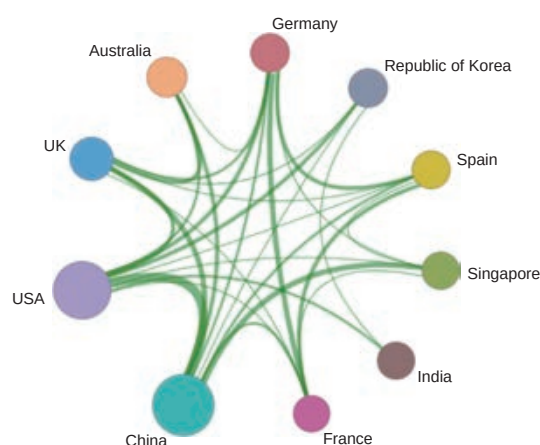


Figure 4.4 Collaboration network among major countries in the engineering research front of “design and discovery of novel smart materials based on machine learning”

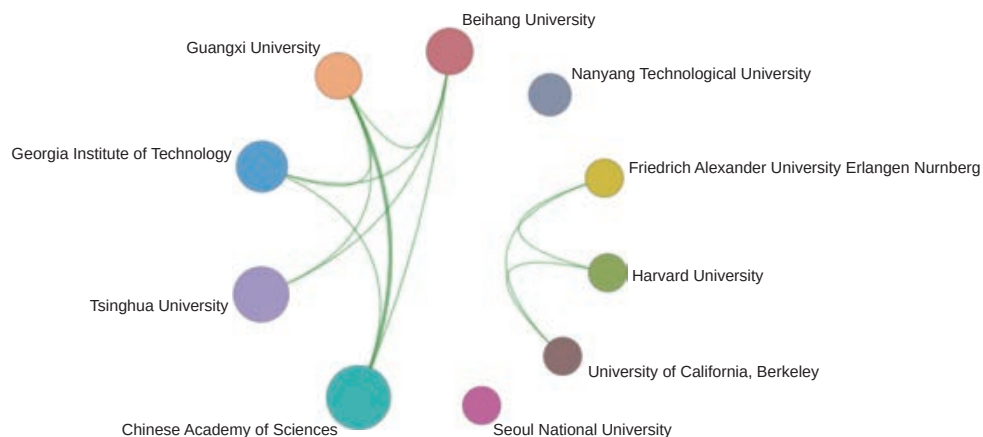


Figure 4.5 Collaboration network among major institutions in the engineering research front of “design and discovery of novel smart materials based on machine learning”

Table 4.9 Countries with the greatest output of citing papers on “design and discovery of novel smart materials based on machine learning”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	4 424	43.34	2022.4
2	USA	1 843	18.06	2022.0
3	UK	652	6.39	2022.2
4	Republic of Korea	638	6.25	2022.3
5	India	616	6.04	2022.4
6	Germany	491	4.81	2022.2
7	Australia	334	3.27	2022.2
8	Canada	315	3.09	2022.2
9	Italy	311	3.05	2022.2
10	Singapore	303	2.97	2022.2

Table 4.10 Institutions with the greatest output of citing papers on “design and discovery of novel smart materials based on machine learning”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	512	26.41	2022.3
2	Tsinghua University	197	10.16	2022.4
3	Zhejiang University	181	9.33	2022.4
4	National University of Singapore	154	7.94	2022.1
5	Shanghai Jiao Tong University	150	7.74	2022.2
6	Beihang University	137	7.07	2022.4
7	Hong Kong Polytech University	132	6.81	2022.3
8	Massachusetts Institute of Technology	127	6.55	2021.5
9	Fudan University	118	6.09	2022.1
10	Nanyang Technological University	116	5.98	2022.3

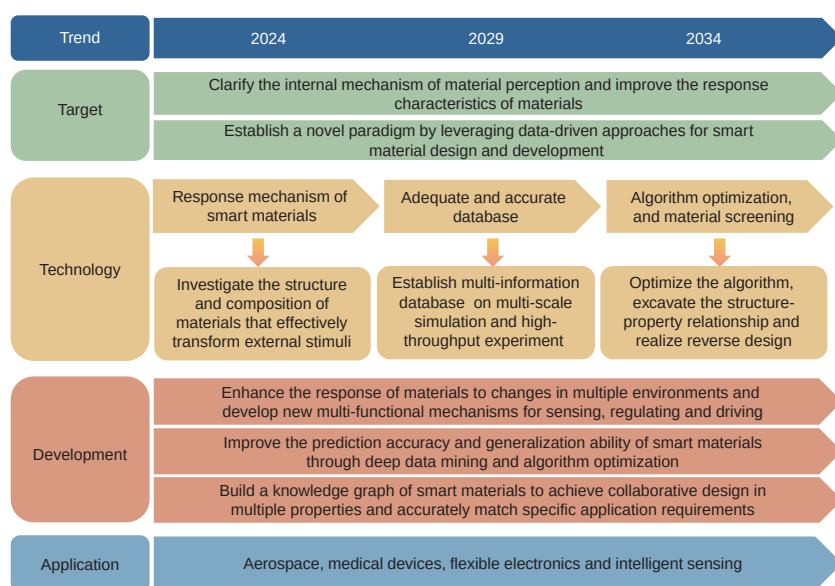


Figure 4.6 Roadmap of the engineering research front of “design and discovery of novel smart materials based on machine learning”

the development of data-driven materials. It is necessary to combine multi-scale simulation and high-throughput experimental technology to form a multi-information database to improve the prediction accuracy and generalization ability of smart materials. Based on this technology, through algorithm optimization, the processing ability of machine learning for complex data would be improved. Thus, the structure-property relationships of materials are mined and analyzed to realize the reverse design of materials that accurately match specific application requirements. The development of new smart materials will surely be empowered by machine learning, which is expected to realize the self-learning and evolution ability. Starting from the actual needs, it can realize the personalized and customized manufacturing of material functions, and develop an autonomously improved material system, which will be widely used in fields such as aerospace, medical devices, flexible electronics, and intelligent sensing.

4.1.2.3 Purification and separation of similar elements in metallurgical processes

Similar metal elements often exist in the process of enrichment and mineralization, forming co-associated mineral resources, which increases the difficulty of purification in the metallurgical extraction process. With the continuous consumption of high-quality mineral resources, treated metallurgical minerals are becoming more complex, and the requirements for the purity of metallurgical products are becoming more stringent, making the efficient separation of similar elements more challenging. The main methods used for the separation of similar elements include solvent extraction, ion exchange, selective precipitation, fractional crystallization, molten salt rectification, and molten salt extraction. When similar elements are separated in complex systems, multiple methods are often used to achieve efficient separation. Even when dealing with the same system, the separation methods are different because the content of similar elements changes. Multiscale separation methods also correspond to complex separation processes and new separation mechanisms, but in situ characterization techniques may help to clarify the complex separation dynamics and element migration processes. Additionally, due to the similar chemical properties, the similar elements are likely to cause mutual loss in the separation process, and thus the development of efficient separation of new systems and reagents to improve separation efficiency has become a core issue. Using host-guest theory, machine learning, and molecular dynamics simulations can save resources and accelerate the design and synthesis of new extractants. The depth of the separation process is related to the quality of the metallurgical product and affects the properties of the back-end prepared materials. The separation process is also the main discharge outlet for wastewater, waste residue, and harmful salt in the metallurgical process, which faces great environmental protection pressure.

The countries and institutions with the greatest output of core papers on the “purification and separation of similar elements in metallurgical processes” are shown in Tables 4.11 and 4.12, respectively. Among the countries with the greatest output of core papers, China ranks the highest, accounting for more than 40%, followed by the USA. The Chinese Academy of Sciences is the greatest producer of core papers, followed by four other Chinese universities: Jiangxi University of Science and Technology, University of Science and Technology of China, University of Science and Technology Beijing, and Tsinghua University. The collaboration networks among major countries and institutions are shown in Figures 4.7 and 4.8. China is at the core of the network of cooperation in this field, forming cooperative relations with many countries, especially with the USA. The USA is also an important connection point in the network, working with all countries except India, Canada, and Japan. The cooperation between institutions is mainly observed among various universities in China, with the Chinese Academy of Sciences at the core of the cooperation network in this field, working most closely with the University of Science and Technology of China. As seen in Tables 4.13 and 4.14, China is the country with the largest number of citing papers, with 2 589 papers, accounting for approximately half of the total number. The USA ranked second with 11.76% of the citing papers. Among the major institutions with the greatest output of citing papers, the Chinese Academy of Sciences ranked first, and several other Chinese universities with metallurgical majors, such as Central South University, University of Science and Technology Beijing, Northeastern University, Kunming University of Science and Technology, and Jiangxi University of Science and Technology, are all in top ten. China produced the greatest output of core papers and citing papers, indicating that Chinese scholars are prolific and track the trends in this research front.

Table 4.11 Countries with the greatest output of core papers on “purification and separation of similar elements in metallurgical processes”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	62	41.89	3 082	49.71	2019.5
2	USA	27	18.24	1 691	62.63	2019.6
3	Belgium	16	10.81	713	44.56	2019.1
4	Australia	10	6.76	1 086	108.60	2020.0
5	France	10	6.76	424	42.40	2019.4
6	Finland	8	5.41	471	58.88	2019.5
7	India	7	4.73	542	77.43	2019.6
8	Canada	7	4.73	461	65.86	2020.1
9	Japan	5	3.38	426	85.20	2020.6
10	Sweden	5	3.38	218	43.60	2019.8

Table 4.12 Institutions with the greatest output of core papers on “purification and separation of similar elements in metallurgical processes”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	28	18.92	1 279	45.68	2019.0
2	Katholieke Universiteit Leuven	16	10.81	713	44.56	2019.1
3	Jiangxi University of Science and Technology	7	4.73	248	35.43	2019.3
4	University of Science and Technology of China	6	4.05	236	39.33	2018.7
5	University of Science and Technology Beijing	5	3.38	183	36.60	2019.6
6	Tsinghua University	4	2.70	204	51.00	2021.0
7	Duke University	3	2.03	291	97.00	2019.0
8	Khalifa University of Science & Technology	3	2.03	174	58.00	2019.7
9	Chalmers University of Technology	3	2.03	149	49.67	2018.7
10	Aalto University	3	2.03	132	44.00	2019.0



Figure 4.7 Collaboration network among major countries in the engineering research front of “purification and separation of similar elements in metallurgical processes”

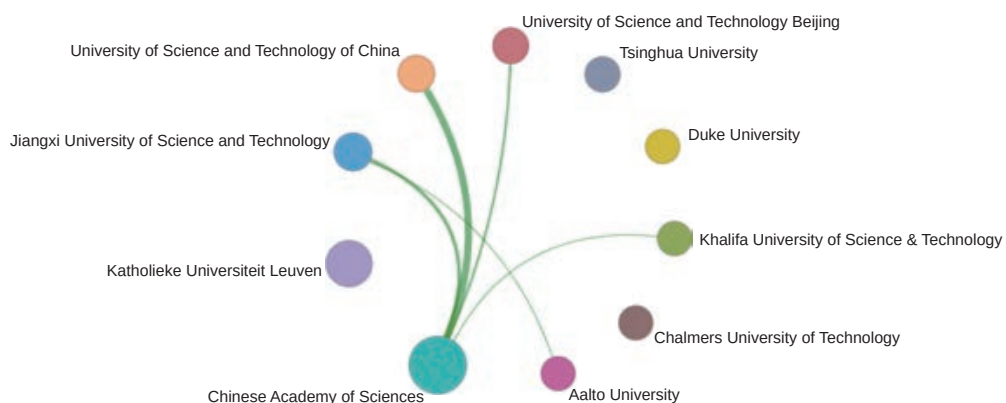


Figure 4.8 Collaboration network among major institutions in the engineering research front of “purification and separation of similar elements in metallurgical processes”

Table 4.13 Countries with the greatest output of citing papers on “purification and separation of similar elements in metallurgical processes”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 589	49.77	2022.0
2	USA	612	11.76	2021.8
3	India	404	7.77	2021.9
4	Russia	249	4.79	2021.6
5	Australia	224	4.31	2021.7
6	Germany	208	4.00	2021.7
7	Iran	201	3.86	2022.0
8	France	192	3.69	2021.4
9	Canada	189	3.63	2021.7
10	UK	172	3.31	2021.8

The emerging industries with new energy and information technologies bring new opportunities for the metallurgical industry. Efficient, low-carbon emission, high-quality similar-element separation technology is the main research direction for the “purification and separation of similar elements in metallurgical processes” (Figure 4.9). It is necessary to establish differential-regulation separation theories of similar elements, form a new mechanism of targeting-recognition, and develop highly selective separation reagents and new technologies. By revealing the distribution and migration rules of each element in the separation process, it may be possible to trace the formation and diffusion of pollution sources.

Table 4.14 Institutions with the greatest output of citing papers on “purification and separation of similar elements in metallurgical processes”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	480	32.24	2021.9
2	Central South University	175	11.75	2022.1
3	Russian Academy of Sciences	127	8.53	2021.6
4	University of Science and Technology of China	112	7.52	2022.2
5	University of Science and Technology Beijing	103	6.92	2022.0
6	China University of Geosciences	87	5.84	2021.9
7	Northeastern University	86	5.78	2021.8
8	Kunming University of Science and Technology	86	5.78	2022.0
9	Jiangxi University of Science and Technology	84	5.64	2021.9
10	Katholieke Universiteit Leuven	81	5.44	2020.8

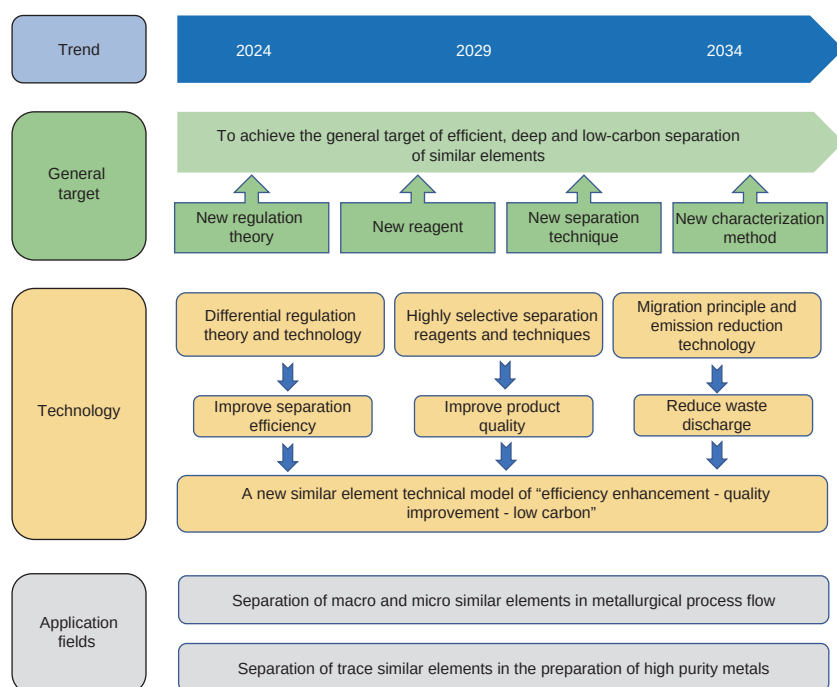


Figure 4.9 Roadmap of the engineering research front of “purification and separation of similar elements in metallurgical processes”

4.2 Engineering development fronts

4.2.1 Trends in the Top 10 engineering development fronts

The top ten engineering development fronts, as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering, are shown in Table 4.15. “Efficient customized preparation technology for high-performance multi-component alloy materials” was mined from ThemeScape patent maps. “Digital and intelligent non-ferrous metal metallurgy processes” and “design of high-temperature flexible lightweight thermal insulation materials” were directly recommended by experts. The other fronts were chosen by a panel of experts according to ThemeScape patent maps. Just as research fronts energy related technologies are also recognized, including solid-state batteries, sodium-ion batteries, large-scale preparation of hydrogen storage materials, and seawater electrolysis for hydrogen production, with a significant increase in the number of patents for all-solid-state batteries and sodium-ion batteries (Table 4.16).

(1) Key materials and preparation technology for all-solid-state batteries

All-solid-state batteries are transformative battery technologies that use solid electrolytes to replace the liquid electrolytes in traditional lithium-ion batteries, which are expected to provide higher energy density, improved safety, and longer cycle lifetimes. The development of all-solid-state batteries involves the improvement of solid electrolytes and cathode/anode materials, interface optimization, and cell formation techniques. Solid electrolyte materials are the core of all-solid-state batteries and can be categorized into three main types: sulfide, oxide, and polymer electrolytes. Among them, sulfide electrolytes are the focus of global research owing to their high ionic conductivity and low interfacial resistance, whereas oxide electrolytes are also receiving attention for their high chemical stability. Polymer electrolytes, valued for their flexibility and ease of processing, also have significant application potential. In terms of cathode materials, oxides and lithium iron phosphate remain the primary choices, with interface modification being used to eliminate the space charge layer effect. Meanwhile, sulfur-based cathodes are also considered promising for increasing energy density. For the anode, silicon and lithium metal, with their high theoretical

Table 4.15 Top 10 engineering development fronts in the chemical, metallurgical, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Key materials and preparation technology for all-solid-state batteries	1 616	3 468	2.15	2021.1
2	Key technologies and equipment for multi-process integrated additive manufacturing of metals	2 305	6 483	2.81	2021.1
3	Green long-life seawater electrolysis hydrogen production systems and seawater mineral resources	710	1 143	1.61	2021.1
4	Large-scale preparation process of high-performance solid-state hydrogen storage materials and the design of efficient solid-state hydrogen storage systems	1 036	1 737	1.68	2021.0
5	Digital twin steel manufacturing technology	476	944	1.98	2021.2
6	Efficient customized preparation technology for high-performance multi-component alloy materials	724	1 009	1.39	2020.8
7	Design and industrialization of core materials for sodium-ion batteries	1 306	3 628	2.78	2021.5
8	Design, control, and preparation of efficient electromagnetic wave-absorbing materials	855	2 939	3.44	2020.7
9	Digital and intelligent non-ferrous metal metallurgy processes	326	708	2.17	2020.7
10	Design of high-temperature flexible lightweight thermal insulation materials	274	418	1.53	2020.7

Table 4.16 Annual number of core patents published for the Top 10 engineering development fronts in the chemical, metallurgical, and materials engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Key materials and preparation technology for all-solid-state batteries	126	170	272	268	342	438
2	Key technologies and equipment for multi-process integrated additive manufacturing of metals	177	247	327	494	560	500
3	Green long-life seawater electrolysis hydrogen production systems and seawater mineral resources	73	82	92	117	157	189
4	Large-scale preparation process of high-performance solid-state hydrogen storage materials and the design of efficient solid-state hydrogen storage systems	116	123	130	194	241	232
5	Digital twin steel manufacturing technology	55	45	53	86	92	145
6	Efficient customized preparation technology for high-performance multi-component alloy materials	92	97	106	122	161	146
7	Design and industrialization of core materials for sodium-ion batteries	103	136	111	145	282	529
8	Design, control, and preparation of efficient electromagnetic wave-absorbing materials	140	107	122	162	178	146
9	Digital and intelligent non-ferrous metal metallurgy processes	57	44	38	52	63	72
10	Design of high-temperature flexible lightweight thermal insulation materials	38	38	49	49	49	51

specific capacity, are considered critical for enhancing the overall energy density of the batteries. Global research trends in all-solid-state battery development are centered around several key areas: ① solid electrolytes that combine high lithium-ion conductivity with high chemical and electrochemical stability; ② high strength, high ionic conductivity, ultra-thin solid electrolyte films; ③ high-capacity, low-strain cathode and anode materials that are compatible with solid electrolytes at the interface; ④ interface modification techniques; ⑤ cost-effective, scalable production methods for key materials. Overall, the development of all-solid-state batteries is gradually moving toward commercialization and is expected to become the dominant next-generation energy storage technology.

(2) Key technologies and equipment for multi-process integrated additive manufacturing of metals

Multi-process integrated manufacturing technology integrates multiple additive manufacturing processes and other manufacturing processes into the same system to produce complex, high-performance metal or alloy components and achieve integrated technology solutions. Through refined process optimization, this technology not only improves the precision and automation level of manufacturing but also enhances the flexibility of structural design and effectively simplifies the production process, providing efficient and high-quality solutions for the manufacturing of complex metal components. This technology has demonstrated its revolutionary potential in multiple key industries, particularly in automobiles, aerospace, military equipment, and rail transit. With the continuous advancement of technology and the improvements in cost-effectiveness, this technology is expected to be applied in a wider range of manufacturing fields. The development of metal multi-process integrated manufacturing technology focuses on the following key directions: ① collaborative metal additive manufacturing of multi-material and multi-process components, achieving high performance and multiple functions through optimal process combinations; ② integrated composite manufacturing of additive and subtractive materials, using additive and subtractive technologies alternately in the same process to improve production efficiency and part quality; ③ developing an intelligent composite processing control system that uses multiscale modeling, simulation, machine learning, and artificial intelligence technologies to improve the intelligence level of the manufacturing process.

(3) Green long-life seawater electrolysis hydrogen production systems and seawater mineral resources

Considering the scarcity of freshwater resources and the importance of carbon sinks, hydrogen production through seawater

electrolysis is a key pathway for generating “green hydrogen” in the future. Additionally, seawater is the largest reservoir of magnesium on Earth, and the development and use of seawater-based magnesium resources offer significant economic benefits. Presently, there are three major pathways for hydrogen production from seawater electrolysis: ① desalination followed by conversion to freshwater, integrating pure water into commercial electrolysis systems; ② adding alkaline substances to seawater to precipitate hydroxides and reduce corrosion reactions in the anode region; ③ direct seawater electrolysis, which involves the direct electrolysis of untreated seawater and the extraction and use of magnesium resources through cathodic reactions. However, the complex composition of seawater poses numerous challenges for direct electrolysis, including anode corrosion and cathode scaling. Compared with pure water electrolysis, both alkaline seawater electrolysis and direct seawater electrolysis typically reduce the service lifetimes of electrodes and systems, necessitating their redesign to meet the operational demands of seawater conditions. Current research on seawater electrolysis primarily focuses on the following areas: ① mechanistic studies of anode corrosion in alkaline seawater electrolysis and the development of long-life anti-corrosion electrodes; ② development of high-activity, fluctuation-resistant cathodes for alkaline seawater electrolysis; ③ investigating scaling mechanisms in direct seawater electrolysis and the development of anti-scaling cathodes; ④ technology for manufacturing high-power seawater electrolysis systems.

(4) Large-scale preparation process of high-performance solid-state hydrogen storage materials and the design of efficient solid-state hydrogen storage systems

Solid-state hydrogen storage systems represent a highly promising avenue of research in the field of hydrogen storage applications, offering a significant advantage in terms of their substantial hydrogen storage capacity, reliance on abundant raw materials, and cost-effectiveness. Furthermore, solid-state hydrogen storage systems can be transported at atmospheric pressure, thereby markedly enhancing the safety factor associated with hydrogen storage and transportation. This enables solid-state hydrogen storage systems to serve as a supplementary or partial replacement for existing high-pressure/liquid-state hydrogen storage and transportation systems in specific scenarios. Concurrently, the transport efficiency of solid-state hydrogen storage systems is approximately four times that of 20 MPa trailer trucks, and the effective coverage radius has also expanded to over 500 km. Of greater significance, however, is the fact that solid-state hydrogen storage systems can also be applied in fixed hydrogen refueling stations and smart buildings. This reduces the safety requirements of hydrogen storage and improves overall hydrogen storage safety. Nevertheless, the large-scale preparation process of high-performance solid-state hydrogen storage materials remains a challenge. ① The development of efficient synthesis processes, which entails the adjustment of core control factors for preparing solid-state hydrides under the coupling effects of the reaction atmosphere, mechanical forces, and catalysts, as well as the development of hydrogenation preparation processes for solid-state hydrides induced by mechanical forces under active reaction atmospheres, is aimed at promoting the efficient, low-cost, and rapid synthesis of solid hydride hydrogen storage materials. ② The design of an efficient solid-state hydrogen storage system requires the design of efficient catalysts for different systems, along with the adjustment of the amount of catalyst added. ③ In the pursuit of a large-scale preparation system, it is necessary to continuously improve catalysts and processes, with the ultimate goal of developing an integrated system. The goal is to achieve a production capacity of 100 tons/year of solid-state hydride hydrogen storage materials, significantly reducing hydrogen costs and promoting the large-scale application of hydrogen energy. ④ There is motivation to design a demonstrative solid-state hydrogen storage material application system. The objective is to develop a solid-state hydrogen storage and transportation system with a capacity of at least one ton of hydrogen, to decouple the space and heat required for hydrogen charging and discharging, and to demonstrate the system’s feasibility in practice.

(5) Digital twin steel manufacturing technology

The long production process, strong coupling of processes, extreme production conditions, complex internal physical changes, and chemical reactions in the steel industry make it extremely difficult to model, control, and optimize the production process, which in turn affects the improvement of production quality and efficiency. The rapid development of digital twins in industrial scenarios provides new opportunities for transforming and upgrading the steel industry. Digital twin technology can improve production efficiency and product quality by creating digital copies of physical entities to integrate data, models, and knowledge, ultimately providing authentic data, events, and responses for new process validation and technology introduction. The construction of digital

twins in the steel industry mainly includes data, modeling, service, platform construction, software, and security. Research on digital twins in the steel industry mainly focuses on the collection, transmission, storage, and establishment of multi-dimensional high-fidelity models for multi-source heterogeneous data. Steel companies have developed digital twin models and systems, integrating functions such as factory comprehensive displays, production process simulation monitoring, process parameter optimization design, multi-level batching optimization, product quality management, intelligent equipment operation and maintenance, and intelligent safety management. The development trends of digital twin technology in the field of steel manufacturing mainly include the following aspects: ① data security, ensuring data remains stable and is not leaked during the collection, transmission, storage, and other stages; ② model development, raising model accuracy by combining mechanisms, data, and knowledge for modeling; ③ establishing and constantly improving the standard system of digital twins to help them develop in an orderly way.

(6) Efficient customized preparation technology for high-performance multi-component alloy materials

Considering their extensive applications in critical sectors such as aerospace, automotive manufacturing, and energy systems, high-performance multi-component alloy materials have been a crucial driver in the development of efficient customized preparation technologies, promoting modern industrial and technological progress. Efficient customized preparation technologies are designed to address the challenges associated with conventional alloy fabrication methods, including compositional heterogeneity, low production efficiency, unstable performance, and the difficulty of simultaneously optimizing multiple performance attributes. Through the refinement of alloy composition design and the integration of advanced preparation methodologies and process control techniques, these technologies enable the rapid, precise, and controllable synthesis of high-performance multi-component alloys. The development of such advanced technologies must prioritize not only the precise control and uniform distribution of alloy compositions but also the cost-effectiveness and high throughput of the process, thus accommodating the complex and dynamic requirements of various applications. Key development areas include: ① optimizing alloy composition through computational modeling and experimental validation, with a focus on elucidating the synergistic interactions between constituent elements to enhance material performance; ② advancing preparation processes, such as rapid solidification, powder metallurgy, and laser-based techniques, to improve both production efficiency and material integrity; ③ exerting fine control over the microstructural evolution during processing through the manipulation of key process parameters, thereby enhancing material performance, compositional uniformity, and structural stability; ④ developing robust performance evaluation frameworks and predictive models that inform alloy design and process optimization, thereby facilitating the customized development of materials tailored to specific application requirements.

(7) Design and industrialization of core materials for sodium-ion batteries

Recently, sodium-ion batteries have emerged as an important alternative to Li-ion batteries owing to their resource advantages, cost-effectiveness, and environmental friendliness. Innovation and breakthroughs in core material technology are key to the industrial application of sodium-ion batteries. Research on the design and industrialization of core materials for sodium-ion batteries mainly focuses on the following areas: ① Advanced electrode material structure design: fine-tuning of cathode materials, such as layered oxides, polyanions, Prussian blue analogs, carbon, and sodium metal anode materials, through doping, coating, cross-linking, pore structure, defects, and interfaces, to improve safety, rate, cycling, and energy performance while exploring new materials and mechanisms. ② Developing new Na-ion electrolytes: screening/synthesizing new Na-ion solutes, solvents, and additives to meet diverse requirements such as a wide voltage window, long cycling life, fast charging-discharging, wide temperature range, and flame resistance, as well as analyzing the intrinsic relationships among sodium-ion solvation structures, cathode/anode interfaces, and electrochemical performance. ③ Deep cultivation of solid-state battery technology: developing safe, efficient, and cost-effective sodium-ion solid electrolytes to improve ion conductivity and overcome the challenges of solid-solid interfaces. In addition, mature manufacturing processes for lithium-ion batteries can be referenced to tailor and optimize the production of sodium-ion batteries. These future directions include the application of cell-to-pack technology in the field of sodium-ion batteries, using aluminum foil for both cathode and anode, maximizing the grouping efficiency of battery packs, effectively compensating for the relative lack of energy density, fully leveraging cost competitiveness, and opening up new paths for the industrial application of sodium-ion batteries.

(8) Design, control, and preparation of efficient electromagnetic wave-absorbing materials

Electromagnetic stealth technology uses materials and structures that weaken and absorb the intensity of electromagnetic waves, thereby minimizing the probability of being discovered and identified by the detection system. The demand for high-performance electromagnetic stealth materials and structures in aerospace, aviation, detection, communications, and other industries and high-end equipment is growing. With the increasing complexity of electromagnetic environments, such as high temperature, high salt fog, and high stress, it is urgent to develop electromagnetic materials and components that function under a range of extreme service conditions. Research is mainly focused on: ① the composition design, development, and preparation of advanced multi-spectrum electromagnetic functional materials; ② the design and optimization of advanced service electromagnetic materials; ③ the functional integration of advanced electromagnetic simulation systems and the improvement of special-shaped electromagnetic simulation algorithms; ④ the functional optimization and compatible design of magnetoelectric materials under service coupling conditions and the preparation of components; ⑤ the service verification and cycle optimization of multi-frequency electromagnetic stealth materials and components; ⑥ the service coupling mechanism of related electromagnetic materials and components.

(9) Digital and intelligent non-ferrous metal metallurgy processes

Numerical intelligent non-ferrous metal metallurgy process optimization and design combine artificial intelligence, industrial internet, and other information technologies with metallurgical industry process control. This can be achieved using a multi-objective intelligent optimization control system based on master/auxiliary fuzzy control, enabling the optimization of key process parameters, energy consumption, and other indicators. The digital intelligent transformation of the non-ferrous metal metallurgy industry is not only a technological change but also provides an efficient information management and analysis platform and promotes enterprise management. Through the centralized method of data-driven decision-making, the data islands of each process in the metallurgical process are accessed and connected through information sharing. Data analysis and simulation evaluation are then carried out to accurately understand the bottlenecks and optimization spaces in the production process, achieving lean management of the metallurgical process. With the rapid development of artificial intelligence technology and big data platforms, future research in non-ferrous metal metallurgy based on data intelligence mainly focuses on ① the coupling mechanism of material flow, energy flow, and information flow; ② green smart factory design based on 5G and industrial internet; ③ the application of artificial intelligence-based machine vision technology, which provides a more intuitive and intelligent human-computer interaction experience, making operations more convenient and efficient.

(10) Design of high-temperature flexible lightweight thermal insulation materials

High-temperature flexible lightweight thermal insulation materials have emerged as a critical research frontier in global scientific and industrial sectors, driven by their essential applications in aerospace, energy-efficient construction, energy systems, and extreme environmental conditions. These advanced materials are designed and developed to address the limitations of traditional thermal insulators, such as glass fibers, silicates, and aerogels, which often exhibit brittleness, low durability, and inadequate mechanical strength under high-temperature conditions. By introducing multifunctional composites and optimizing their microstructures, a material system is achieved that synergistically combines high-efficiency thermal insulation with beneficial mechanical properties. These materials must not only satisfy the thermal insulation criteria in extreme environments but also exhibit low density, flexibility, and eco-friendliness to accommodate a wide range of applications. Key technical directions include: ① conducting comprehensive investigations into the intrinsic relationship between the material microstructures and their thermophysical properties, precisely manipulating internal structures while optimizing interfacial designs to enhance the cooperative effects on both thermal efficiency and mechanical integrity under extreme conditions; ② developing innovative composite fabrication techniques, such as 3D printing, nanostructured design, and aerogel modification, to achieve an optimal balance among thermal insulation efficiency, lightweight characteristics, and mechanical robustness while enhancing flexibility and shape formability; ③ exploring novel intelligent insulating materials through the incorporation of phase change substances or thermoregulating films that facilitate the self-adaptive modulation of thermal insulation performance, aimed at maximizing energy use efficiency; ④ investigating recyclable and biodegradable thermal insulation materials, coupled with green, cost-effective manufacturing processes, to promote sustainability in large-scale applications.

4.2.2 Interpretations for three key engineering development fronts

4.2.2.1 Key materials and preparation technology for all-solid-state batteries

All-solid-state batteries are among the most cutting-edge technologies in the field of energy storage. Notably, they effectively overcome the limitations of liquid electrolytes in terms of energy density, safety, and thermal stability. As the demand for high-energy density, safe, and long-lasting batteries continues to grow in portable electronic devices, electric vehicles, and energy storage systems, the development of all-solid-state batteries has garnered significant attention from the global scientific and industrial communities. Major initiatives, including NEDO of Japan, JCESR/DOE of the U.S., Horizon 2020 of the European Union, and the Ministry of Science and Technology of China, have prioritized the advancement of all-solid-state battery technology.

The core of all-solid-state battery technology lies in the development of solid electrolyte materials. These materials must not only possess high ionic conductivity but also exhibit high chemical and electrochemical stability with electrode materials, thereby reducing interfacial resistance and preventing side reactions. Although research on all-solid-state batteries can be traced back to the early 20th century, significant progress has only been made since the 2000s. A breakthrough came in 2011 with the development of the LGPS sulfide electrolyte, which achieved an ionic conductivity surpassing that of liquid electrolytes. This milestone spurred many automotive and battery manufacturers, as well as startups, to develop high-performance sulfide-based all-solid-state batteries.

Despite this progress, all-solid-state battery technology still faces several challenges. First, the properties and performance of solid electrolytes have not reached the levels required for commercialization. Although some material systems exhibit high lithium-ion conductivity, their stability in air, with solvents, and with lithium metal needs to be improved. Furthermore, solid electrolytes, as inactive materials, occupy a large proportion of the cell, which limits the increase in energy density. Thus, reducing the thickness of the electrolyte membrane is an urgent priority. From a mechanical perspective, the volumetric changes of cathode and anode materials during charge and discharge can lead to failure of the solid-solid interface contact. Additionally, the interfacial stability between solid electrolytes and electrode materials has yet to be fully resolved, particularly during repeated cycles, where increasing interfacial resistance leads to rapid performance degradation. Therefore, the development of high-capacity, low-strain cathode and anode materials is crucial to enhancing the comprehensive performance of all-solid-state batteries. Finally, achieving the commercialization of all-solid-state batteries requires the development of low-cost, scalable production technologies for key material systems. With continuous innovation in key materials and breakthroughs in technology, all-solid-state batteries are expected to play a critical role in the future energy landscape. In particular, they hold great promise to replace existing lithium-ion batteries in electric vehicles and large-scale energy storage systems, driving revolutionary advancements in energy technology.

Globally, the patent distribution in the engineering research and development of “key materials and preparation technology for all-solid-state batteries” shows significant regional differences and trends in institutional concentration. In terms of regional distribution (Table 4.17 and Figure 4.10), Japan dominates the field, with a patent publication volume far surpassing that of other countries, accounting for 52.72% of the total patents, and having the highest citation frequency. This indicates Japan’s notable leading position in the development of all-solid-state battery materials. Republic of Korea and China rank second and third, with patent shares of 23.89% and 21.35%, respectively. Western countries, such as the USA, France, Canada, and Germany, have relatively fewer patents in this field. However, with their strong foundational capabilities, the potential for future development in these regions should not be underestimated. In terms of institutional distribution (Table 4.18 and Figure 4.11), Toyota Motor Corporation holds the highest number of patent publications in this field, with 378 patents, accounting for 23.39% of the total, reflecting its dominant position in all-solid-state battery technology. LG Chem Ltd. and Hyundai Motor Company rank second and third, demonstrating the continued research and development investment by Republic of Korea companies in this sector. Other large companies, such as Panasonic Corporation and Samsung Electronics Co., Ltd., also have a substantial accumulation of patents in this area. In summary, patents related to the development of key materials for all-solid-

Table 4.17 Countries with the greatest output of core patents on “key materials and preparation technology for all-solid-state batteries”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Japan	852	52.72	2 119	61.10	2.49
2	Republic of Korea	386	23.89	554	15.97	1.44
3	China	345	21.35	771	22.23	2.23
4	USA	31	1.92	41	1.18	1.32
5	France	9	0.56	5	0.14	0.56
6	Canada	4	0.25	6	0.17	1.50
7	Germany	3	0.19	0	0.00	0.00
8	Belgium	2	0.12	1	0.03	0.50
9	India	1	0.06	0	0.00	0.00

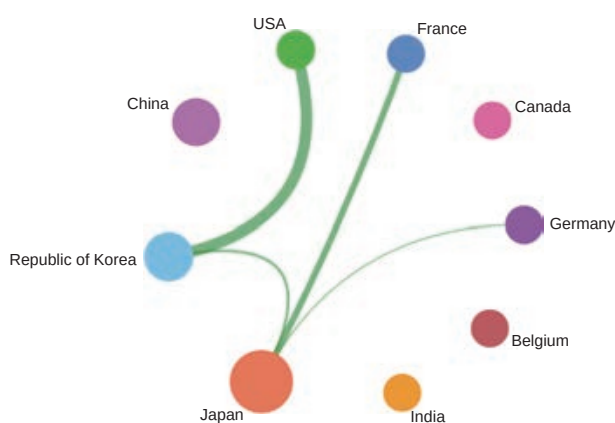


Figure 4.10 Collaboration network among major countries in the engineering development front of “key materials and preparation technology for all-solid-state batteries”

Table 4.18 Institutions with the greatest output of core patents on “key materials and preparation technology for all-solid-state batteries”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Toyota Motor Corporation	378	23.39	829	23.90	2.19
2	LG Chem Ltd.	114	7.05	265	7.64	2.32
3	Hyundai Motor Company	92	5.69	124	3.58	1.35
4	Kia Corporation	90	5.57	112	3.23	1.24
5	Panasonic Corporation	75	4.64	372	10.73	4.96
6	Showa Denko Packaging Co., Ltd.	48	2.97	90	2.60	1.88
7	Samsung Electronics Co., Ltd.	44	2.72	41	1.18	0.93
8	Nissan Motor Co., Ltd.	38	2.35	18	0.52	0.47
9	Renault Group	33	2.04	18	0.52	0.55
10	Maxell, Ltd.	30	1.86	38	1.10	1.27

state batteries are primarily concentrated in Japan, Republic of Korea, and China, with Japanese companies showing the most outstanding performance in terms of technical accumulation and leadership. The patent competition among major institutions is intense, and collaboration may be a crucial pathway to further advancing this technology.

With strong policy support from various parties and the rapid development of key core materials and technologies, the next decade may be a critical period for breakthroughs in all-solid-state battery technology (Figure 4.12). Advances in new materials and processes offer a promising opportunity for significant progress in the industrialization of all-solid-state batteries. Optimizing the comprehensive properties of solid electrolyte materials remains the core focus, while achieving continuous production of ultra-thin films through wet coating processes is also important. Additionally, the development of high-capacity, low-strain cathode and anode materials and their low-cost, scalable production are crucial. Of particular importance is the optimization of interfacial properties between these materials and the electrolytes, which is necessary to ensure the safety and overall electrochemical performance of all-solid-state batteries. These advancements should enable their broad application in electric vehicles, portable electronic devices, energy storage systems, and specialized fields.

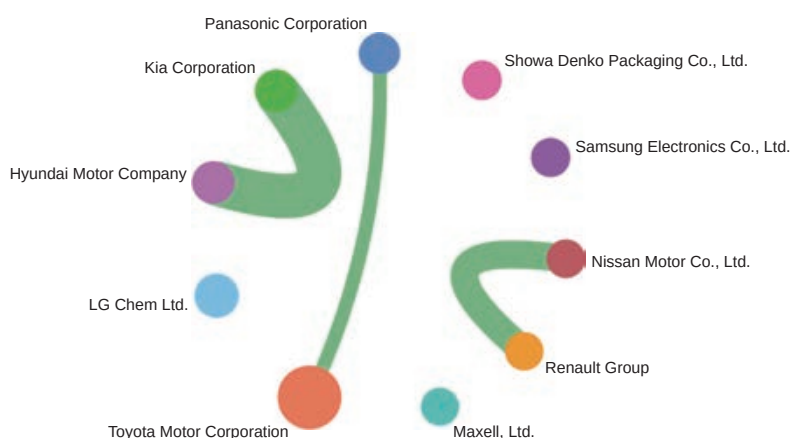


Figure 4.11 Collaboration network among major institutions in the engineering development front of “key materials and preparation technology for all-solid-state batteries”

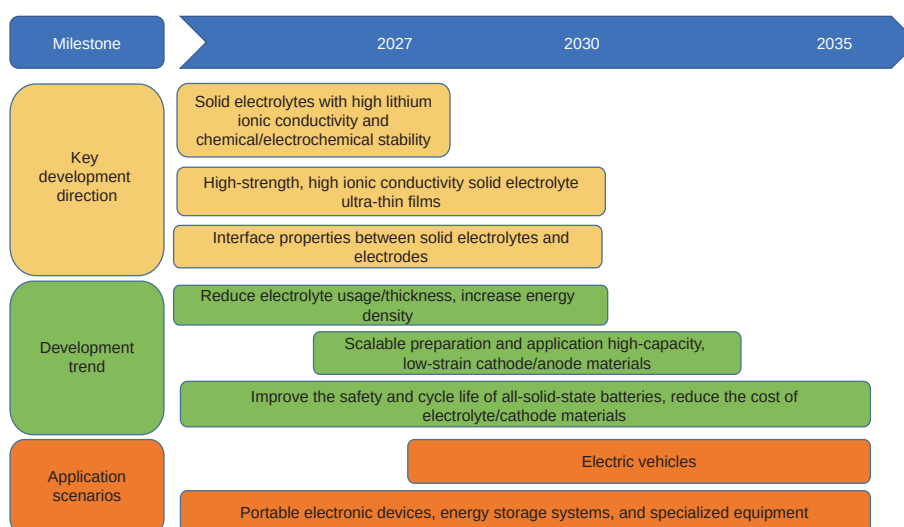


Figure 4.12 Roadmap of the engineering development front of “key materials and preparation technology for all-solid-state batteries”

4.2.2.2 Key technologies and equipment for multi-process integrated additive manufacturing of metals

Metal additive manufacturing is one of the most important branches of additive manufacturing technology. Metal powder or wires are used as raw materials, high-energy beams (laser, electron, and arc plasma beams) are used as cutting tools, computer 3D CAD data models are used as the structural basis, and the principle of discrete stacking is employed to melt and stack materials layer by layer under the control of software and numerical control systems to manufacture high-performance metal components. Compared with traditional subtractive manufacturing processes, such as turning, milling, planning, and grinding, as well as equal-material manufacturing processes, such as casting, forging, and welding, metal additive manufacturing technology is characterized by its high design freedom, ability to form complex structures, short product realization cycle, high product performance, and high material utilization rate. It is widely used in aerospace, biomedicine, automotive manufacturing, and power energy fields, which account for over 50% of the entire additive manufacturing market. With the continuous expansion of applications brought about by technological progress, metal additive manufacturing has developed into a variety of process technologies, including laser melting deposition (LMD), electron beam melting (EBM), selective laser melting (SLM), and directed energy deposition (DED).

With the increasing demand for lightweight components, high-end performance, and complex structures, as well as changes in agile manufacturing and high-end digital manufacturing environments, the development of multi-process integrated additive manufacturing technology for metal is becoming increasingly important. This technology integrates various metal additive manufacturing (such as laser metal additive manufacturing and arc additive manufacturing) and traditional manufacturing (such as mechanical processing and heat treatment), helps optimize the manufacturing process, and has the advantages of high processing precision, high automation, strong structural ease, and a reduced process chain. Thus, efficient and high-quality production of complex metal components can be achieved. To date, this technology has been widely applied and researched in fields such as automobile manufacturing, aerospace, national defense, and rail transit. With the continuous growth in technical capabilities and the decrease in hardware system costs, this technology has broad market prospects and is expected to be widely applied in numerous fields, promoting the development of next-generation manufacturing.

From Table 4.19, China is leading in the number of patents in this field, accounting for over 70% of the total patents; the remaining patents are mostly from developed regions such as Europe, the USA, Japan, and Republic of Korea. Table 4.20 shows that China's institutions working in this field are concentrated in technology research and development, such as universities and research institutes. This also suggests to some extent that China still needs to strengthen the transformation of technological achievements, especially in applications and investment in downstream fields. Additionally, in terms of international cooperation and exchanges related to this field, China's openness is not sufficient, as shown in Figure 4.13. It is necessary to further expand the international influence of related fields and the cooperation among domestic research institutions, especially the cooperation between upstream and downstream fields, as well as among related industries, as illustrated in Figure 4.14.

In the next decade, with the development and maturity of additive manufacturing technology, digital control technology for materials, thermal coupling simulation technology, and internet technology, “key technologies and equipment for multi-process integrated additive manufacturing of metals” are expected to expand and be widely applied in commercial applications, comprehensively promoting the optimization of overall performance, weight reduction, heat dissipation, high integration, and agile manufacturing cycles of equipment. As shown in Figure 4.15, the technological frontier mainly focuses on several aspects: ① Metal additive manufacturing with multi-material and multi-process collaboration: using the optimal additive process combination to achieve the manufacturing and forming of multiple types of metal materials, simultaneously achieving multi-material designs and layouts, multi-level structural innovation and printing inside complex integral components, and high-performance and multifunctional components. ② Integrated composite manufacturing of additive and subtractive materials: alternating the use of additive and subtractive technologies in the same manufacturing process. Using additive manufacturing to achieve layer-by-layer forming, and using subtractive manufacturing to improve the surface quality and stress state, balances the rapid prototyping of additive manufacturing with the high precision of subtractive manufacturing. At the same time, the combination achieves single-setup clamping of parts and need not to switch between processes, which significantly improves production efficiency and part quality. ③ Intelligent composite processing control system: combining advanced technologies, such as multiscale modeling and

Table 4.19 Countries with the greatest output of core patents on “key technologies and equipment for multi-process integrated additive manufacturing of metals”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	1 630	70.72	4 242	65.43	2.60
2	USA	292	12.67	1 489	22.97	5.10
3	Germany	96	4.16	234	3.61	2.44
4	Japan	69	2.99	134	2.07	1.94
5	France	55	2.39	73	1.13	1.33
6	India	22	0.95	8	0.12	0.36
7	UK	19	0.82	111	1.71	5.84
8	Republic of Korea	15	0.65	9	0.14	0.60
9	Sweden	12	0.52	19	0.29	1.58
10	Russia	12	0.52	6	0.09	0.50

Table 4.20 Institutions with the greatest output of core patents on “key technologies and equipment for multi-process integrated additive manufacturing of metals”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Shanghai Jiao Tong University	53	2.30	236	3.64	4.45
2	Aerospace Research Institute of Special Materials and Processing Technology	52	2.26	120	1.85	2.31
3	Huazhong University of Science and Technology	47	2.04	208	3.21	4.43
4	Xi'an Jiaotong University	45	1.95	166	2.56	3.69
5	Central South University	33	1.43	187	2.88	5.67
6	Institute of Metal Research, Chinese Academy of Sciences	31	1.34	87	1.34	2.81
7	General Electric Company	29	1.26	216	3.33	7.45
8	Tianjin University	28	1.21	66	1.02	2.36
9	Jilin University	26	1.13	92	1.42	3.54
10	Harbin Institute of Technology	26	1.13	52	0.80	2.00

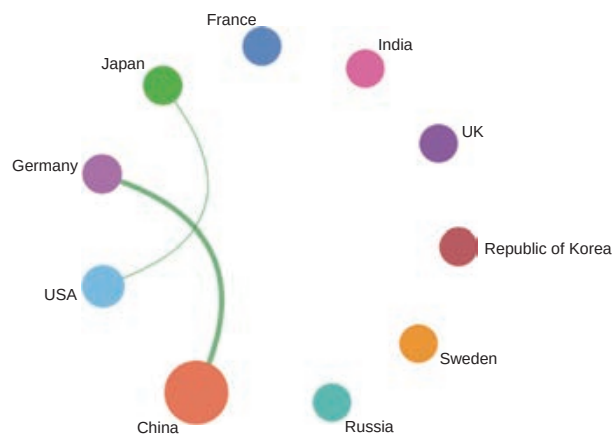


Figure 4.13 Collaboration network among major countries in the engineering development front of “key technologies and equipment for multi-process integrated additive manufacturing of metals”

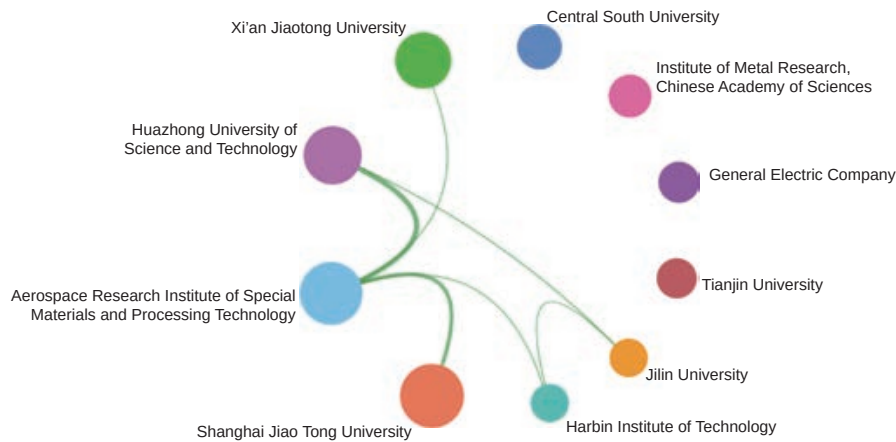


Figure 4.14 Collaboration network among major institutions in the engineering development front of "key technologies and equipment for multi-process integrated additive manufacturing of metals"

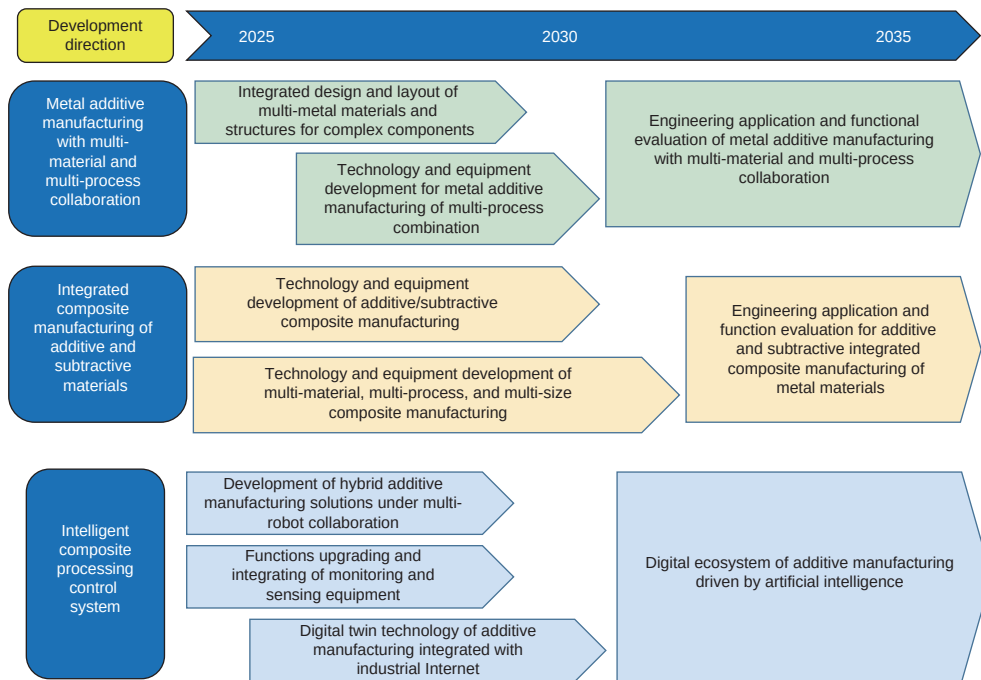


Figure 4.15 Roadmap of the engineering development front of "key technologies and equipment for multi-process integrated additive manufacturing of metals"

simulation, machine learning, and artificial intelligence, to more effectively link information with physical processes. This strategy focuses on developing hybrid additive manufacturing solutions under the cooperation of multi-robot development, improving the function and integration of monitoring and sensing equipment, integrating the industrial internet into the digital twin of additive manufacturing, and supporting the establishment and improvement of the digital ecosystem of additive manufacturing.

4.2.2.3 Green long-life seawater electrolysis hydrogen production systems and seawater mineral resources

Water electrolysis is considered a promising technology for generating "green hydrogen," aligning with international carbon

neutrality goals and supporting a sustainable production-consumption-regeneration cycle for hydrogen. However, given that global pure water resources are severely limited (approximately 2.53% of the total water), large-scale hydrogen production via pure water electrolysis may exacerbate freshwater shortages. In contrast, seawater, which constitutes approximately 96.5% of the Earth's water resources, offers a promising alternative for hydrogen production. Despite this potential, the presence of Cl^- (~0.5 mol/L) in seawater poses significant challenges because it can be easily oxidized at the anode under electrolysis conditions, leading to the formation of corrosive chlorine-containing substances that can damage anode materials. Moreover, during the electrolysis process, the pH near the cathode can deviate significantly, causing Ca^{2+} and Mg^{2+} in seawater to combine with the OH^- produced at the cathode, resulting in the formation of insoluble compounds such as $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$. These precipitates can cover the active sites of catalysts, leading to electrode deactivation. Additionally, the inherent fluctuations of renewable energy sources complicate the operation of electrolyzers, as they cannot quickly respond to changes, disrupting the reaction and thermal equilibria and degrading the performance of the electrolytic cells. Therefore, the development of energy-efficient, long-life seawater electrolysis systems is crucial for the large-scale application of seawater electrolysis for hydrogen production.

Research on seawater electrolysis for hydrogen production began in the mid-20th century, but progress remained relatively slow until the early 21st century. In recent years, however, the rapid rise of the hydrogen energy industry has brought this technology into the spotlight, attracting significant attention from research institutions and companies worldwide, thus accelerating development. Currently, several companies are actively engaged in the field of seawater electrolysis for hydrogen production, including Lhyfe in France, Environmental Resources Management in the UK, Shenzhen Hydrogen Energy Technology Co., Ltd. in China, and Dongfang Electric Corporation in China. Foundational research in this area is primarily focused on developing long-life electrode materials, addressing corrosion and scaling issues caused by impurity ions in seawater, understanding reaction mechanisms, and creating novel seawater electrolysis devices that can withstand operational fluctuations.

Asian countries dominate this field, with China significantly leading in both the number of patent disclosures and the proportion of citations, far surpassing other countries (Table 4.21). There is currently with relevant technologies subject to international restrictions and core technologies yet to be made public. Germany and the USA exhibit notably higher average citation frequencies for their patents than other countries, indicating their continued technological leadership in this area. According to Table 4.22, China's primary patent-producing entities include both academic institutions and industrial enterprises, suggesting a strong integration between industry, academia, and research in seawater electrolysis. Coastal research institutions in China, such as the Dalian Institute of Chemical Physics of Chinese Academy of Sciences (CAS), Qingdao University of Science & Technology, Ningbo Institute of Materials Technology and Engineering of CAS, and Tianjin University, are highly focused on advancing seawater electrolysis technology. On the corporate side, the China Huaneng Clean Energy Research Institute and China Shipbuilding

Table 4.21 Countries with the greatest output of core patents on "green long-life seawater electrolysis hydrogen production systems and seawater mineral resources"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	556	78.31	916	80.14	1.65
2	Republic of Korea	71	10.00	50	4.37	0.70
3	Japan	17	2.39	29	2.54	1.71
4	USA	15	2.11	74	6.47	4.93
5	Saudi Arabia	9	1.27	11	0.96	1.22
6	Australia	5	0.70	2	0.17	0.40
7	Germany	4	0.56	17	1.49	4.25
8	Norway	4	0.56	4	0.35	1.00
9	Brazil	4	0.56	0	0.00	0.00
10	Canada	4	0.56	0	0.00	0.00

Industry Corporation are among the leading entities. The widespread distribution of research institutions further underscores the significant research importance and value of seawater electrolysis hydrogen production systems.

With the rapid development of the hydrogen energy industry and strong policy support, the seawater electrolysis industry is entering a critical period of strategic opportunity. Over the next decade, this technology is expected to expand and reach large-scale application (Figure 4.16). Although significant research has been conducted on the design and fabrication of electrodes and systems for seawater electrolysis, numerous technical and scientific challenges remain unresolved. In the context of equipment upgrades and technological advancements, the research and development supply chain for seawater electrolysis electrode materials faces new challenges and demands. Alkaline seawater electrolysis is likely to remain the primary focus of development

Table 4.22 Institutions with the greatest output of core patents on “green long-life seawater electrolysis hydrogen production systems and seawater mineral resources”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Huaneng Clean Energy Research Institute	21	2.96	17	1.49	0.81
2	Dalian Institute of Chemical Physics, CAS	17	2.39	24	2.10	1.41
3	Qingdao University of Science & Technology	14	1.97	15	1.31	1.07
4	China Shipbuilding Industry Corporation	14	1.97	12	1.05	0.86
5	Ningbo Institute of Materials Technology and Engineering, CAS	10	1.41	44	3.85	4.40
6	Tianjin University	9	1.27	7	0.61	0.78
7	Qingdao Zhongshi Daxin Energy Technology Co., Ltd.	9	1.27	6	0.52	0.67
8	Harbin Institute of Technology	8	1.13	3	0.26	0.38
9	Shenzhen University	7	0.99	27	2.36	3.86
10	Chinese Academy of Fishery Sciences	7	0.99	14	1.22	2.00

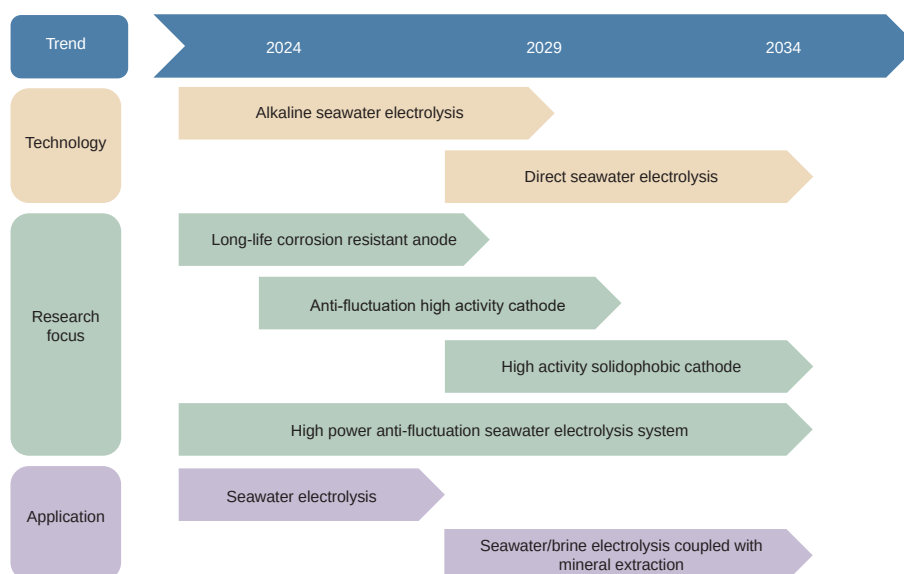


Figure 4.16 Roadmap of the engineering development front of “green long-life seawater electrolysis hydrogen production systems and seawater mineral resources”

in the short term. However, critical breakthroughs are urgently needed in the design and development of long-life, corrosion-resistant anodes, the enhancement of cathode activity and resilience against fluctuations, and the creation of high-power seawater electrolysis systems capable of withstanding operational fluctuations. In the long term, developing direct seawater electrolysis systems based on highly active and solidophobic cathodes may be of great significance, representing the future direction of the field. Moreover, the primary objective of seawater electrolysis will continue to be hydrogen production in the near term. However, as materials and systems continue to evolve, seawater electrolysis technology is expected to advance toward a dual-purpose approach: the simultaneous production of green hydrogen and the extraction of mineral resources from seawater or brine (concentrated seawater). The economic benefits derived from the extraction of seawater mineral resources could significantly reduce the cost of seawater electrolysis, thereby paving the way for its large-scale application.

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Chapter 5 Energy and Mining Engineering Fronts



5.1 Engineering research fronts

5.1.1 Trends in the Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 5.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geological resource science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, “research on integrated CO₂ capture and *in situ* utilization”, “discovery of high ionic conductivity solid electrolytes”, and “study on large models of power system operation and maintenance” represent energy and electrical science, technology, and engineering research fronts; “principles of compact fusion and tritium resource conversion”, “simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods”, and “experimental research on the application of a new type of heat pipe reactor in space reactors” represent nuclear science, technology, and engineering research fronts; “high-resolution remote sensing ore-forming information extraction based on deep learning”, “research on the sources and ore-forming processes of orogenic gold deposits”, and “*in situ* conversion mechanism of Chang 7 shale oil” represent geological resource science, technology, and engineering research fronts; and “Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”, “intelligent fine characterization of deep oil and gas reservoirs”, and “optimization of sensor networks in intelligent monitoring systems for coal mine safety” represent research fronts of mining science, technology, and engineering. The annual publication status of the core papers related to each front from 2018 to 2023 is shown in Table 5.2.

Table 5.1 Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on integrated CO ₂ capture and <i>in situ</i> utilization	50	4 890	97.80	2020.2
2	Principles of compact fusion and tritium resource conversion	2	89	44.50	2018.0
3	High-resolution remote sensing ore-forming information extraction based on deep learning	21	4 103	195.38	2020.7
4	Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization	312	54 332	174.14	2019.9
5	Discovery of high ionic conductivity solid electrolytes	559	26 142	46.77	2021.2
6	Study on large models of power system operation and maintenance	307	6 737	21.94	2021.4
7	Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods	24	433	18.04	2019.8
8	Experimental research on application of a new type of heat pipe reactor in space reactors	39	889	22.79	2020.8
9	Research on the sources and ore-forming processes of orogenic gold deposits	42	2 145	51.07	2020.7
10	<i>In situ</i> conversion mechanism of Chang 7 shale oil	18	1 105	61.39	2020.2
11	Intelligent fine characterization of deep oil and gas reservoirs	1 088	12 237	11.25	2021.0
12	Optimization of sensor networks in intelligent monitoring systems for coal mine safety	4	200	50.00	2021.0

Table 5.2 Annual number of core papers published for the Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Research on integrated CO ₂ capture and <i>in situ</i> utilization	7	13	7	12	10	1
2	Principles of compact fusion and tritium resource conversion	2	0	0	0	0	0
3	High-resolution remote sensing ore-forming information extraction based on deep learning	0	3	6	7	5	0
4	Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization	65	67	64	72	38	6
5	Discovery of high ionic conductivity solid electrolytes	37	66	75	120	108	153
6	Study on large models of power system operation and maintenance	13	24	49	47	82	92
7	Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods	4	5	8	5	2	0
8	Experimental research on the application of a new type of heat pipe reactor in space reactors	1	3	12	10	11	2
9	Research on the sources and ore-forming processes of orogenic gold deposits	3	5	11	11	7	5
10	<i>In situ</i> conversion mechanism of Chang 7 shale oil	2	1	9	5	0	1
11	Intelligent fine characterization of deep oil and gas reservoirs	107	121	159	198	250	253
12	Optimization of sensor networks in intelligent monitoring systems for coal mine safety	0	1	0	1	2	0

(1) Research on integrated CO₂ capture and *in situ* utilization

The integrated carbon dioxide (CO₂) capture and *in situ* utilization refers to the technology by which the adsorbed CO₂ is converted into high-value products without undergoing traditional temperature and pressure swing desorption processes. The core of this technology is to complete CO₂ capture and conversion within the same material system, thereby eliminating processes such as CO₂ separation, purification, storage, and transportation. Theoretically, it can significantly reduce costs and energy consumption, and simplify system processes. The CO₂ capture process can utilize solid adsorption or solution absorption to capture CO₂ and couple it with catalytic conversion. The mainstream technical route uses adsorption catalytic dual functional materials composed of alkali/alkaline earth metal oxide adsorbents and precious metal or transition metal catalysts. The adsorbed CO₂ is converted *in situ* through reaction processes such as methanation, reverse water gas gasification, and methane dry reforming. The main research directions and development trends of integrated CO₂ capture and *in situ* utilization include: ① high-performance, low-cost, and long-life dual functional materials, as well as the coupling reaction mechanism of CO₂ adsorption and *in situ* catalytic conversion; ② process parameter optimization, as well as renewable energy coupling technology; ③ large-scale demonstration application and technical and economic analysis of real scenarios.

(2) Principles of compact fusion and tritium resource conversion

In the field of magnetic confinement fusion, compact nuclear fusion refers to a technology aimed at developing smaller and cost-effective fusion reactors. In the past, several large tokamak devices have been constructed internationally to explore fusion research. However, these devices require significant financial investment. Additionally, the International Thermonuclear Experimental Reactor (ITER), a collaborative international project, demands extensive cooperation and shared financial responsibilities among multiple parties. In recent years, breakthroughs in high-temperature superconducting magnet technology have significantly reduced the economic costs associated with fusion reactors, leading to rapid advancements in compact fusion reactor technology. Compared to traditional nuclear fission, nuclear fusion offers a cleaner and safer energy source. However, for the most feasible deuterium-tritium fusion, the required tritium is extremely scarce in nature. To generate sufficient tritium for

future fusion reactors, lithium blankets are designed within the reactor, where neutrons produced by the fusion reaction bombard the lithium to produce tritium, and develop an efficient tritium recovery system to recycle tritium resources.

(3) High-resolution remote sensing ore-forming information extraction based on deep learning

The high-resolution remote sensing ore-forming information extraction technology based on deep learning utilizes deep learning models to automatically identify and extract key geological interpretation information (such as mineralized zones, rock types, and geological structures), ore-forming information extraction (alteration, hydroxyl), and mineral resource-related features from high-resolution remote sensing images. Combined with multi-source data fusion and feature optimization, it achieves precise location and classification of potentially mineralized areas, thereby enhancing the efficiency and accuracy of mineral exploration and providing a scientific basis for resource exploration. The main research directions in this field include feature extraction and identification, multi-source data fusion, spatiotemporal change analysis, and intelligent geological interpretation. Feature extraction and identification involve using deep learning models to automatically extract mineral and geological features from remote sensing images. Multi-source data fusion integrates multi-scale, multi-modal remote sensing data to enhance the capability of ore-forming information identification. Spatiotemporal change analysis uses time-series remote sensing data to monitor dynamic changes in geological bodies and identify potential mineralization activities. Intelligent interpretation automatically generates geological interpretation reports by coupling multi-source information to assist experts in mineral potential assessment. In the future, the high-resolution remote sensing ore-forming information extraction technology based on deep learning will usher in a series of significant development trends. These trends include obtaining more comprehensive ore-forming information through multi-source data fusion and spatiotemporal analysis, enhancing the interpretability and credibility of models to ensure the transparency and reliability of interpretation results, and realizing efficient analysis and mining of massive data through the deep integration of remote sensing big data and artificial intelligence. This technology will play an increasingly important role in mineral resource exploration, ore-forming prediction, and potential evaluation.

(4) Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization

The integrated development and utilization of oil and gas with wind-light-heat-storage refers to the synergistic use of different energy forms during the development and production processes in oil and gas fields. This approach aims to improve energy efficiency and reduce environmental impact. By comprehensively considering the characteristics and advantages of renewable energy sources (such as wind, solar, and geothermal energy) and energy storage technologies, adopting comprehensive planning, shared infrastructure, energy storage and conversion technologies, intelligent management systems, and policy incentives, it aims to achieve multi-energy complementarity and efficient energy utilization in the construction of smart oilfields. The main research directions in this field include: ① the study of integrated development of multi-energy complementary microgrids and oil and gas production; ② theoretical research on the collaborative optimization and control of production in multi-energy complementary microgrids; ③ research on the source-network-load-storage configuration and production scheduling optimization methods for multi-energy microgrids in oil and gas fields. The independent mechanisms and optimization methods for oil and gas, renewable energy (such as wind and solar), and energy storage are gradually evolving into collaborative mechanisms and optimization methods for oil and gas with wind-light-heat-storage. With the advancement of information technology, the integrated development of oil and gas with wind-light-heat-storage is progressing towards efficient simulation, rapid decision-making, and intelligent control.

(5) Discovery of high ionic conductivity solid electrolytes

Compared to organic liquid electrolytes, solid-state electrolytes have a wider electrochemical window and higher safety, making them an important development direction for future power batteries and energy storage batteries. Nowadays, one of the main application bottlenecks of all-solid-state batteries is the limited charging and discharging rates. The strong ion interactions in bulk solid electrolytes and the high impedance at electrolyte-electrode interfaces lead to migration energy barriers that are 10 times higher than those in liquid electrolytes, retarding the charging and discharging processes. High Li-ion conductivity solid electrolytes are generally composed of inorganic ionic compounds. Based on their stable ion transport channels and good

mechanical adaptability at the interface, sulfur-based solid electrolytes exhibit a lithium-ion conductivity greater than 10 mS/cm at room temperature, which is comparable to commercial liquid electrolytes. By designing the electrolyte composition and studying interfacial stability, the reaction and diffusion energy barriers can be reduced, thereby further improving the lithium-ion conductivity of solid electrolytes. The development directions for electrolyte composition design are to optimize the chemical composition and design the crystalline structure, aiming to increase the number of ion conduction channels and reduce the ion-ion interactions to provide favorable conditions for the free diffusion of lithium ions. Research on interfacial stability primarily develops in the direction of interface passivation layers, coating layers, and alleviation of interfacial stress. It is worth noting that the physicochemical processes, such as ion transport and interface electrochemistry between solid electrolyte phases and electrodes, exhibit distinct coupling characteristics of the chemical field, electric field, and force field. By comprehensively considering the multi-field coupling effect, the experimental studies and theoretical models of solid-state electrolytes under real working conditions can effectively reveal the failure and runaway mechanisms in practical applications, which is an important direction for the development of high-ionic conduction solid-state electrolytes in the future.

(6) Study on large model of power system operation and maintenance

Power system is one of the largest and most complex man-made system in the world. In the context of developing a new type of power system, a large amount of distributed energy resources and flexible loads are integrated, leading to high dimensionality, nonlinearity, and dynamicity in system operation and maintenance. Traditional static modeling and centralized optimization methods can hardly satisfy the requirements in terms of calculation efficiency and accuracy.

The state-of-the-art AI techniques, represented by large-scale models, are promising in addressing the aforementioned problems. Generally speaking, large-scale models refer to neural networks with an extremely large parameter scale that can learn complex patterns from diversified data sets. For example, these models can extract patterns from power system time series measurements, images, and topologies to support system operation and maintenance. In a narrower sense, large-scale models refer to large language models (LLMs), such as ChatGPT, which can integrate and create multi-domain knowledge through the interactions between the model and users, and can also serve as an effective way of supporting power system operation and maintenance.

There exist several issues in the research on large-scale power system AI models: ① Fine-tuning of large-scale models based on limited data samples. Compared to the vast amount of textual information available on the Internet, the sample size of power system operational data, especially the data samples under extreme operating conditions, is much less to train a large-scale AI model from scratch. It is important to study how to efficiently train large-scale AI models based on limited data samples. ② Robustness and interpretability of large-scale AI models. The nature of these models is to learn statistical rules based on deep neural network with a hyperscale number of parameters, the process of which is hard to interpret and may generate inaccurate results. Such a characteristic is contrary to the reliability requirements of power system operation. ③ Data security. Power system operational data is highly sensitive and secured. Training AI models with power system data may lead to data security concerns.

(7) Simulation and testing of principles of glass solidification (vitrification) and other nuclear waste disposal methods

The high-level liquid waste treatment technology is the key technology at the back end of nuclear fuel reprocessing and one of the challenges in the sustainable development of nuclear energy in China. Glass solidification (vitrification) is currently the only industrialized high-level radioactive waste liquid treatment technology in the world, mainly including electrical heating ceramic furnaces and the cold crucible glass solidification technology, of which cold crucible technology, as the fourth-generation glass solidification process, is considered to be the most promising vitrification technology. The composition of high-level waste liquid is complex, containing more than 20 components. When it experiences a temperature change of nearly a thousand degrees Celsius with the base glass, complex physical and chemical reactions and phase transformations occur, and the transformation from high-level waste liquid glass compound to glass state is realized. The simulation of the conversion process from the compound to the glass state is the theoretical basis for the safe and efficient operation of the glass curing furnace. With the increase of burnup, the content of fission products and actinides in the spent fuel will rise, leading to high levels of radioactivity, high decay heat, and

high salt content in the high-level waste liquid from the power reactor. This will also significantly increase the content of refractory substances such as Zr and Mo in the glass curing produced by fission and precious metals, resulting in the accumulation of a large amount of precious metals at the bottom of the furnace and causing the blockage of the bottom discharge. The cold crucible, because of its unique induction heating method, can effectively solve these problems. It is necessary to draw on the experience of electric melting furnaces, focusing on basic problem research, long-term equipment and process verification, as well as cold crucible glass curing formula verification and performance research.

(8) Experimental research on the application of a new type of heat pipe reactor in space reactors

Compared with traditional chemical power and solar power, the nuclear reactor power source is one of the preferred solutions for deep space exploration because of its high energy density, long working life, no need for light and oxidant, and other advantages. Since the 1950s, the USA and Russia have designed a variety of nuclear reactor power supply schemes, such as ROMASHK, BUK, TOPAZ, and TOPAZ-2 from Russia, as well as the nuclear auxiliary power system SNAP-10A and Kilopower from the USA. However, as a high-altitude flight system, it is significantly limited by weight and volume. Therefore, it is necessary to reduce the reactor volume by improving heat transfer efficiency. The aviation nuclear power device based on the heat pipe small reactor can precisely solve this problem. With the development of aviation nuclear power systems, it will be applied to strategic cruise missile propulsion systems, nuclear cargo aircrafts, and nuclear propulsion in the future. The heat pipe reactor has become a focal point of research in the field of space nuclear reactors. Different from the traditional reactor design, the heat pipe reactor design offers strong flexibility and innovation. The use of different alkali metal heat pipes and thermoelectric conversion modes has a direct impact on the system power and the overall system quality, among which the thermoelectric converter plays a decisive role in the lifespan of the whole system, and it is possible to combine heat pipes with a variety of different thermoelectric conversion mode. The heat pipe reactor and the modular design are improved for different modules respectively, which reduces the overall system quality and improves the system safety. Therefore, the heat pipe reactor has great development space and potential in the future.

(9) Research on the sources and ore-forming processes of orogenic gold deposits

The classic orogenic gold deposit refers to quartz vein-type gold deposits formed under compression or strike-slip deformation in the accretionary or collisional orogeny at convergent plate margins. In general, the orogenic gold deposit is not simultaneous and has no genetic association with magmatism. The gold in the orogenic gold deposit mainly comes from terrigenous sediments, continental mafic rocks (e.g., komatiites), oceanic crust and its overlying sediments, as well as metasomatized mantle. In the process of sedimentation-diagenesis, gold occurs in arsenic-bearing pyrite in terrigenous sediments, which is released in the subsequent deformation process and extracted by fluid dehydrated from chlorite during progressive metamorphism from greenschist facies to amphibolite facies to form gold-bearing fluids. The fluid activity formed by the dehydration of subducting oceanic crust can extract a large amount of gold elements from the mafic rocks at the bottom of the lithosphere, forming gold bearing fluids. During the metamorphism of the subducted oceanic crust, the gold in gold-bearing sediments can be reactivated and migrated to form gold-bearing fluids. The gold in the metasomatic mantle can also form gold-bearing fluids during brief reactivation events. The gold in these fluids migrates in the form of S and Cl complexes or colloids and deposits in specific locations to form orogenic gold deposits through complex decomposition, metal droplet absorption, and colloid condensation. Thus, current research focuses on understanding the source of gold in orogenic deposits, the mechanisms of gold activation and mobilization, and the processes leading to its efficient concentration and deposition. Advances in this area are expected to result from the application of *in situ* micro-analysis, metal stable isotope, and other experimental techniques.

(10) *In situ* conversion mechanism of Chang 7 shale oil

The *in situ* conversion of shale oil underground at the depth ranging from 300 m to 3 000 m is a physical and chemical process caused by using horizontal drilling and electric heating technology, which converts heavy oil, bitumen, and various organic matter into light oil and gas on a large scale, which can be called an “underground refinery”. *In situ* conversion has significant advantages in CO₂ capture, recoverable resource potential, and the quality of hydrocarbon output. In view of the characteristics of organic matter-rich shale in Chang 7, the efficient conversion technology of underground “horizontal well with electric heating” is an

effective way for development and utilization of shale oil resources.

The origin of over-enrichment of organic matter in the lacustrine basin, the maceral component, and *in situ* conversion kinetics of organic matters are the core scientific problems of *in situ* conversion of shale oil, and the main research directions of *in situ* conversion of shale oil in Chang 7 include the mechanism of formation of organic-rich shale, the *in situ* conversion technology and heat-transfer mechanism, the flow mechanism of *in situ* conversion, and the *in situ* development technology of shale oil.

The organic matter-rich shale in Chang 7 of the Ordos Basin has continuous thickness, high organic matter abundance, and moderate maturity. The shale oil *in situ* conversion of this strata is the most realistic. The future development trend of basic research includes environmental response to organic matter enrichment and the role of the intervention of external substances, maceral component and differential hydrocarbon generation characteristics under energy field, the multi-phase conversion of the heat conduction dynamics of the organic matter, evolution of multi-phase hydrocarbon fluid field and the *in situ* conversion efficiency of hydrocarbon expulsion, the enrichment mechanism and resource distribution of shale oil with low-medium maturity, etc. In terms of engineering technology, the development of stabilized electric heating rods, high-efficiency composite heating technology, heater downhole process, precise and controllable reservoir conversion, the oil recovery process technology, etc. are the future development trends.

(11) Intelligent fine characterization of deep oil and gas reservoirs

The intelligent fine-grained representation methods of deep oil and gas reservoirs refer to the high-precision quantitative description and analysis of the structure, physical properties, and fluid distribution of deep underground oil and gas reservoirs by integrating multiple sources of geophysical data, geologic models, and artificial intelligence algorithms. The aim is to more accurately describe the complex structure of the deep reservoirs and their fluid distribution characteristics, thereby improving the precision of exploration and development efficiency of the oil and gas reservoirs.

The main research directions include: ① using artificial intelligence and machine learning to form a multivariate data fusion method of seismic data, well logging data, core analysis results, etc., in order to construct a more detailed reservoir model; ② establishing a digital model of deep reservoirs to simulate the generation, migration, and accumulation processes of oil and gas based on high-resolution 3D seismic data and geological information; ③ strengthening the application of machine learning and deep learning algorithms to make the prediction of reservoir parameters and identification of fluid distribution more accurate, and integrating different methods to provide a more comprehensive guide to the development of deep oil and gas reservoirs.

With the improvement of computing power and the development of the big data technology, intelligent fine-grained representation methods increasingly rely on real-time data processing and dynamic model updating. The future research trend ① will focus on real-time data acquisition and processing during drilling, and dynamic fine-grained characterization of reservoirs; ② integrated analysis of reservoir properties at different scales; ③ more precise and automated characterization methods to complete the fine-grained characterization of reservoirs with minimal human intervention.

(12) Optimization of sensor networks in intelligent monitoring systems for coal mine safety

The intelligent monitoring system for coal mine safety is a comprehensive system that integrates various sensor technologies, data processing techniques, and communication technologies. Its core function is to continuously monitor environmental parameters within the mine, such as gas concentrations, temperature, humidity, and pressure, in real-time through sensors. The data collected is then transmitted to a central control system via a network. Optimizing the sensor network involves enhancing sensor layout, data transmission efficiency, and information processing capabilities to achieve real-time, efficient, and secure monitoring objectives, thereby ensuring the safety of miners and the proper operation of equipment. The main research directions include sensor layout optimization, data fusion and processing technologies, communication network optimization, and intelligent early warning systems.

In the future, the sensor networks of the intelligent monitoring systems for coal mine safety are expected to develop towards intelligence, automation, and integration. Specific trends include the continuous development of highly intelligent sensors (such

as multifunctional sensors and intelligent monitoring devices) to enhance the diversity and accuracy of data collection; with the development of the Internet of Things (IoT) technology, more sensors will be connected via networks to achieve real-time data sharing and intelligent analysis, thereby forming an efficient safety monitoring network; the utilization of cloud computing and big data analytics will facilitate the storage, processing, and analysis of vast amounts of data, providing decision support for coal mine safety management; and the development of adaptive monitoring systems will automatically adjust the operation of sensors and monitoring strategies based on environmental changes to improve flexibility and responsiveness in monitoring activities.

5.1.2 Interpretations for four key engineering research fronts

5.1.2.1 Research on integrated CO₂ capture and *in situ* utilization

The carbon dioxide (CO₂) capture and utilization (CCU) technology is a key technology to achieve the dual goals of “carbon peaking and carbon neutrality”. However, the traditional CCU process requires a large amount of energy and complex systems for CO₂ desorption, purification, transportation, storage, and subsequent utilization, which greatly restricts the promotion and application of CCU technology. The integrated CO₂ capture and *in situ* utilization (ICCU) technology provides a new strategy by which CO₂ is captured and utilized in the same material. The CO₂ adsorbed is catalytically converted into fuel or chemicals in the adsorption state without the need for desorption, purification, storage, and transportation processes. This can reduce system complexity and greatly improve energy utilization efficiency.

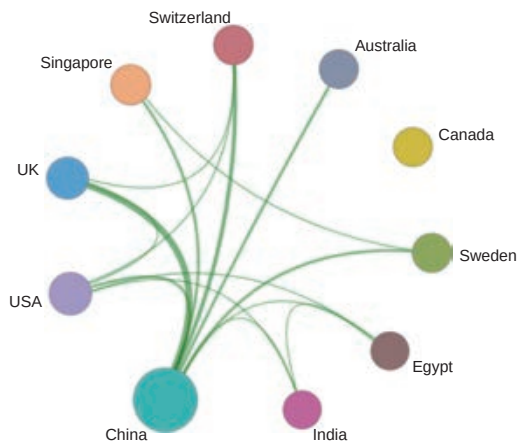
In ICCU technology, the CO₂ capture process can use solid adsorption or solution absorption to capture CO₂ and couple it with catalytic conversion. In 2015, Professor Melis’s group at Columbia University first proposed the concept of adsorption catalytic dual functional materials (DFMs), which were formed by loading calcium oxide adsorbents and ruthenium catalysts on alumina supports to create DFMs. This technical route based on DFMs composed of alkali/alkaline earth metal oxide adsorbents and precious metal or transition metal catalysts, gradually developed into the mainstream ICCU technology. In current research on ICCU technology, the *in situ* catalytic conversion pathway of CO₂ is primarily conducted through reaction processes such as methanation, reverse water gasification, and methane dry reforming. The main research directions of ICCU technology include: ① high-performance, low-cost, and long-life dual functional materials, as well as the coupling reaction mechanism of CO₂ adsorption and *in situ* catalytic conversion; ② process parameter optimization, as well as renewable energy coupling technology; ③ large-scale demonstration applications and technical and economic analysis of real scenarios.

In the research front of “research on integrated CO₂ capture and *in situ* utilization”, the countries with the greatest output of core papers and the citations per paper are China and the USA, respectively (Table 5.3), and there are numerous collaborations among China and the UK (Figure 5.1). Among the top ten institutions in terms of the number of papers published, East China University of Science and Technology and Chinese Academy of Sciences rank top two, while the institutions with the highest citations per paper are China University of Geosciences and Sichuan University (Table 5.4). There are many collaborations between the University of Electronic Science and Technology of China and China University of Geosciences, as well as between the University of Electronic Science and Technology and Sichuan University (Figure 5.2). Countries and institutions with the greatest output of citing papers are shown in Tables 5.5 and 5.6.

For large-scale industrial demonstration applications in the next 5 to 10 years, the ICCU technology will further improve the performance of dual-functional materials, achieve low-cost mass preparation, and reduce operational energy consumption through reactor design, process optimization, and renewable energy coupling. At the same time, through material innovation, application scenarios can be expanded, such as direct air CO₂ capture combined with *in situ* conversion integration, exploring new conversion pathways, such as photocatalysis, electrocatalysis, plasma catalysis, homogeneous catalysis, etc. At present, the ICCU technology has completed laboratory small-scale verification, and it is expected to achieve thousand-ton level demonstration verification, and industrial demonstration by 2034 (Figure 5.3).

Table 5.3 Countries with the greatest output of core papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	37	74.00	3 782	102.22	2020.3
2	USA	7	14.00	738	105.43	2019.0
3	UK	6	12.00	512	85.33	2020.7
4	Singapore	4	8.00	283	70.75	2020.8
5	Switzerland	3	6.00	213	71.00	2019.3
6	Australia	2	4.00	645	322.50	2019.0
7	Canada	2	4.00	165	82.50	2021.0
8	Sweden	2	4.00	130	65.00	2020.0
9	Egypt	1	2.00	155	155.00	2020.0
10	India	1	2.00	155	155.00	2020.0

Figure 5.1 Collaboration network among major countries in the engineering research front of “research on integrated CO₂ capture and *in situ* utilization”Table 5.4 Institutions with the greatest output of core papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	East China University of Science and Technology	4	8.00	269	67.25	2022.0
2	Chinese Academy of Sciences	3	6.00	809	269.67	2018.3
3	University of Electronic Science and Technology of China	3	6.00	752	250.67	2020.0
4	Queen's University Belfast	3	6.00	301	100.33	2021.7
5	National University of Singapore	3	6.00	216	72.00	2021.0
6	Nanjing University of Science and Technology	3	6.00	160	53.33	2020.0
7	China University of Geosciences	2	4.00	672	336.00	2020.0
8	Sichuan University	2	4.00	567	283.50	2019.5
9	University of Science and Technology of China	2	4.00	420	210.00	2019.0
10	University of Southern California	2	4.00	337	168.50	2019.0

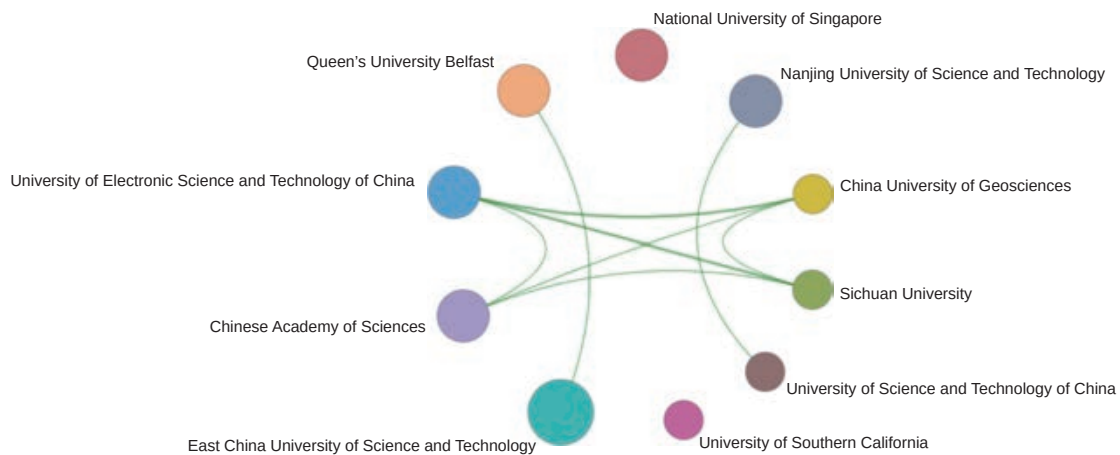


Figure 5.2 Collaboration network among major institutions in engineering research front of “research on integrated CO₂ capture and *in situ* utilization”

Table 5.5 Countries with the greatest output of citing papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	458	57.76	2020.8
2	USA	68	8.58	2020.3
3	Australia	55	6.94	2020.6
4	UK	35	4.41	2020.9
5	India	34	4.29	2020.5
6	Singapore	30	3.78	2021.0
7	Republic of Korea	27	3.40	2020.6
8	Germany	23	2.90	2020.8
9	Japan	22	2.77	2020.6
10	Canada	21	2.65	2021.0

Table 5.6 Institutions with the greatest output of citing papers on “research on integrated CO₂ capture and *in situ* utilization”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	66	24.81	2020.3
2	China University of Geosciences	33	12.41	2020.7
3	University of Science and Technology of China	26	9.77	2020.9
4	Zhengzhou University	24	9.02	2021.1
5	Jiangsu University	23	8.65	2020.8
6	Tianjin University	19	7.14	2020.6
7	University of Electronic Science and Technology of China	18	6.77	2021.3
8	Tsinghua University	16	6.02	2021.4
9	Nanyang Technological University	15	5.64	2020.9
10	Beijing University of Chemical Technology	14	5.26	2020.4



Figure 5.3 Roadmap of the engineering research front of “research on integrated CO₂ capture and *in situ* utilization”

5.1.2.2 Principles of compact fusion and tritium resource conversion

The development of nuclear fusion technology began in the mid-20th century. Early research primarily focused on large-scale fusion devices, which achieved some experimental success. For instance, the Tokamak Fusion Test Reactor (TFTR) was constructed in 1982 at the Princeton Plasma Physics Laboratory in the USA, becoming a prominent device for deuterium-tritium experiments. The TFTR had a major radius of 3.1 meters, a minor radius of 0.96 meters, a magnetic field of 6 T, a plasma current of 3 MA, and a total heating power of 50 MW. In Europe, the Joint European Torus (JET) was built, becoming the first device to conduct 50%:50% deuterium-tritium experiments. Similarly, Japan constructed a large Tokamak device, JT-60 (Torus-60), which, along with TFTR and JET, became one of the three major Tokamak facilities in the world. To further advance fusion energy, the International Thermonuclear Experimental Reactor (ITER) project was initiated, involving collaboration among the European Union, China, Republic of Korea, Russia, Japan, India, and the USA. ITER is the largest and most influential international scientific endeavor in the world to date. These large-scale devices aimed to explore the feasibility of developing and utilizing magnetic confinement fusion energy. However, due to their enormous scale and high costs, commercial applications face challenges. In the 21st century, with breakthroughs in high-temperature superconducting magnet technology, researchers began focusing on the development of compact fusion devices. The compact fusion technology, leveraging high-temperature superconducting magnets, can achieve the miniaturization of fusion devices, significantly reducing the economic costs of fusion development. Notable examples include the SPARC device developed by Commonwealth Fusion Systems, an independent nuclear fusion startup spun out from the Massachusetts Institute of Technology (MIT). The superconducting coils of SPARC are expected to generate a magnetic field of up to 20 T. The SPARC project is scheduled to be completed and conduct deuterium-tritium experiments by 2025. Another example is the STEP device, overseen by the Culham Centre for Fusion Energy in the United Kingdom. Research in compact nuclear fusion heavily relies on international collaboration. This cooperation not only includes bilateral or multilateral agreements between research institutions, but also necessitates multidisciplinary collaboration, involving material science, plasma physics, engineering, etc. In summary, research in compact nuclear fusion is being conducted globally, requiring close cooperation among countries and regions to tackle technological challenges and promote the sustainable development of this field.

In the research front of “principles of compact fusion and tritium resource conversion”, the top three countries in terms of the number of core papers published are the UK, Germany, and Canada (Table 5.7 and Figure 5.4). The primary contributing institutions of core papers are Culham Science Centre, EUROfusion Consortium, Karlsruhe Institute of Technology, Kinectrics Inc., and Open University (Table 5.8). Among the top five institutions, there are more collaborations among Culham Science Centre, EUROfusion Consortium, and Karlsruhe Institute of Technology, as well as more collaborations between Kinectrics Inc. and Open University (Figure 5.5). The main output countries of citing papers are Germany and the USA (Table 5.9), while the main output institutions of citing papers are Karlsruhe Institute of Technology and Max Planck Institute for Plasma Physics (Table 5.10).

The future development of compact nuclear fusion technology will focus on optimizing technology, innovating materials, and scaling up applications. The main areas of focus include:

- 1) Application and optimization of high-temperature superconducting magnets: High-temperature superconducting magnets are critical components of compact nuclear fusion devices. Future research will aim to develop more efficient and stable superconducting magnets to enhance plasma confinement, reduce the size of the devices, and increase energy density. Institutions like the Massachusetts Institute of Technology (MIT) have already made initial breakthroughs in this area, and future efforts will focus on further optimizing magnet materials and cooling technologies.

Table 5.7 Countries with the greatest output of core papers on “principles of compact fusion and tritium resource conversion”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	UK	2	100.00	89	44.50	2018.0
2	Germany	1	50.00	48	48.00	2018.0
3	Canada	1	50.00	41	41.00	2018.0

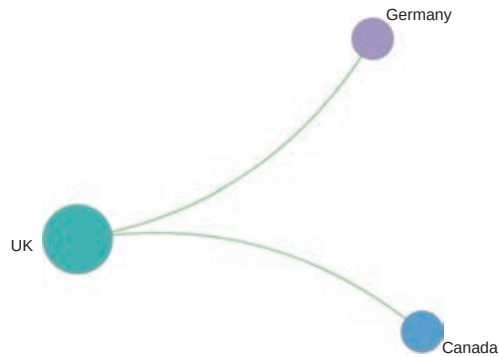


Figure 5.4 Collaboration network among major countries in the engineering research front of “principles of compact fusion and tritium resource conversion”

Table 5.8 Institutions with the greatest output of core papers on “principles of compact fusion and tritium resource conversion”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Culham Science Centre	1	50.00	48	48.00	2018.0
2	EUROfusion Consortium	1	50.00	48	48.00	2018.0
3	Karlsruhe Institute of Technology	1	50.00	48	48.00	2018.0
4	Kinectrics Inc.	1	50.00	41	41.00	2018.0
5	Open University	1	50.00	41	41.00	2018.0

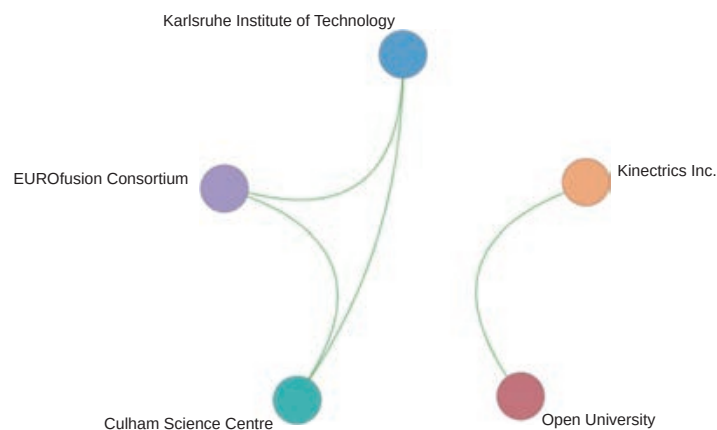


Figure 5.5 Collaboration network among major institutions in the engineering research front of “principles of compact fusion and tritium resource conversion”

Table 5.9 Countries with the greatest output of citing papers on “principles of compact fusion and tritium resource conversion”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	Germany	19	19.59	2020.4
2	USA	19	19.59	2021.6
3	Italy	14	14.43	2021.3
4	UK	12	12.37	2020.9
5	China	10	10.31	2020.8
6	Russia	6	6.19	2020.5
7	Japan	6	6.19	2021.8
8	France	4	4.12	2021.0
9	Romania	3	3.09	2020.0
10	Canada	2	2.06	2022.0

Table 5.10 Institutions with the greatest output of citing papers on the “principles of compact fusion and tritium resource conversion”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Karlsruhe Institute of Technology	10	19.61	2020.6
2	Max Planck Institute for Plasma Physics	6	11.76	2020.2
3	EUROfusion Consortium	5	9.80	2019.8
4	Politecnico di Torino	5	9.80	2022.0
5	Chinese Academy of Sciences	4	7.84	2021.2
6	Culham Science Centre	4	7.84	2020.2
7	China Academy of Engineering Physics	4	7.84	2021.2
8	Italian National Agency for New Technologies, Energy and Sustainable Economic Development	4	7.84	2021.5
9	Sun Yat-sen University	3	5.88	2019.7
10	Bauman Moscow State Technical University	3	5.88	2020.0

2) Development of new materials: The materials used in fusion devices must withstand extremely high temperatures and intense radiation. Future research will focus on developing new materials that are resistant to high temperatures and radiation, thereby improving the lifespan and safety of fusion reactors.

3) Tritium fuel cycle system: The production, recovery, and management of tritium are crucial for the sustained operation of compact nuclear fusion devices. Research directions include efficient tritium production technologies, tritium recovery, and recycling systems.

4) Miniaturization and modularization of reactor design: Developing smaller and modular reactor designs will be a key area of focus, allowing for more flexible and cost-effective fusion devices.

The future trends will involve transitioning from experimental validation to prototype development and commercial exploration. Compact nuclear fusion holds enormous potential for energy security and sustainability. Furthermore, advancements in the fusion technology will drive progress in other high-tech fields. In the future, the compact nuclear fusion technology will prioritize the exploration of high-temperature superconducting magnets, new materials, and tritium fuel cycle systems (Figure 5.6). The technology has vast potential for development and a wide range of application scenarios. It is not only expected to solve the energy crisis but also to drive technological progress and economic development. However, commercial applications still require time and collaborative international efforts.

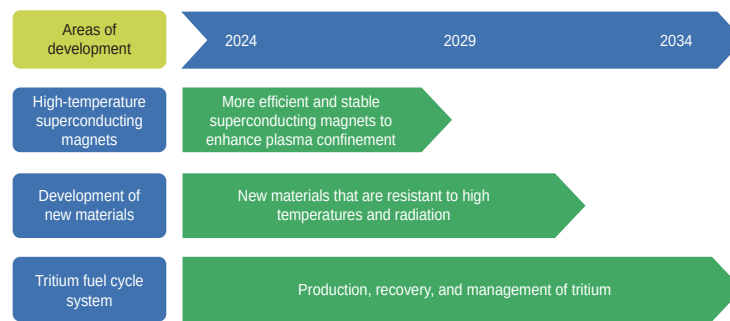


Figure 5.6 Roadmap of the engineering research front of “principles of compact fusion and tritium resource conversion”

5.1.2.3 High-resolution remote sensing ore-forming information extraction based on deep learning

The high-resolution remote sensing ore-forming information extraction technology is an integrated approach that relies on remote sensing image processing, geological information analysis, and deep learning. It is applied in the field of geological mineral exploration. The core of this technology is the use of deep learning algorithms to automatically identify and extract relevant features such as geological interpretations of fault structures, ore-forming information, and mineral resources from high-resolution remote sensing images. By combining multi-source data fusion and feature optimization, precise localization and classification of potentially mineralized areas can be achieved, thereby improving the efficiency and accuracy of mineral exploration and assisting in geological exploration and resource evaluation. The development of ore-forming information extraction technology based on remote sensing images has evolved from traditional image interpretation to automation, multi-source data fusion, and intelligent deep learning algorithms. Initially, remote sensing ore-forming information extraction relied on expert experience and manual interpretation. With the widespread application of high spatial and hyperspectral remote sensing data, the extraction of ore-forming information has gradually shifted towards pixel-based and feature-based automated analysis. New methods such as new RGB combinations, band ratios, and selective principal component analysis have been used to highlight and extract remote sensing alterations related to minerals, achieving indirect mineral identification. In recent years, with the continuous launch of remote sensing satellites equipped with high spatial and hyperspectral resolution optical sensors and the popularization of the UAV remote sensing technology, methods such as weakly supervised object detection, semantic segmentation, and change detection have been employed to achieve high-precision identification and extraction of ore-forming information. In this context, the “artificial intelligence + remote sensing big data” model has become the mainstream direction in the field of ore-forming information extraction. The main research directions include the “spatial-spectral-temporal” joint feature extraction of high-resolution images and the development of automated ore-forming information extraction algorithms based on deep learning. These high-precision, intelligent ore-forming information extraction technologies have an important practical significance and strategic value in mineral resource exploration, national strategic resource security, and other aspects.

In China’s new round of strategic actions for achieving breakthroughs in mineral exploration, there is an emphasis on advancing the integrated remote sensing mineral exploration system that combines satellite, aerial, ground, and subsurface methods. Research has been conducted at three levels: ① For mineralized belts, satellite remote sensing data, particularly the hyperspectral satellite data recently launched by China, is used to select prospective mining areas. ② In key research areas, aerial or drone remote sensing data is employed to pinpoint locations or delineate target areas. ③ At the minefield scale, ground or core spectrometers are used to conduct detailed alteration mineral mapping of the surface or core samples, analyze the ore-forming environment, and identify hydrothermal centers, providing technical support for subsequent mineral exploration deployment.

In the research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”, China ranks first in the number of core papers, with 20 papers accounting for 95.24% of the total. The proportion of papers from other countries is less than 10.00%. Italy ranks second with two core papers, accounting for 9.52% (Table 5.11). Regarding the main output institutions of core papers (Table 5.12), 8 of the top ten institutions are from China, with Wuhan University, the Chinese

Academy of Sciences, and Beihang University occupying the top three positions. China is also the leading country in terms of the number of cited core papers in this research front, accounting for 73.04% of the total. The USA ranks second, with 96 papers, accounting for only 5.98% (Table 5.13). Among the institutions producing the most cited core papers, Wuhan University, the Chinese Academy of Sciences, and Xidian University rank in the top three positions (Table 5.14). Collaborations in this field are primarily between China, Italy, the USA, and the Netherlands (Figure 5.7). There are institutional collaborations among Wuhan University, Nanjing University of Information Science and Technology, the Italian Space Agency, and China University of Mining and Technology (Figure 5.8).

In the next 5 to 10 years, the high-resolution remote sensing ore-forming information extraction based on deep learning will usher in a series of significant development trends (Figure 5.9). The optimization and innovation of deep learning models will lead to the emergence of more models specifically optimized for remote sensing data characteristics, such as lightweight models and self-supervised learning models, which will enhance the accuracy and efficiency of ore-forming information extraction. Multi-source data fusion and joint analysis using the “time-space-spectrum” combined analysis model will achieve a more comprehensive extraction of ore-forming information. The coordinated application of drones and ground-based remote sensing will enhance exploration accuracy through high-precision data collection and ore-forming feature analysis. The integration of satellite remote sensing, aerial remote sensing, ground surveying, and deep exploration will form an integrated mineral exploration system (satellite-air-ground-depth integrated remote sensing exploration system), which will improve the capability and application level of ore-forming information extraction at different scales. The deep integration of remote sensing big data and artificial intelligence will enable efficient analysis and mining of massive datasets. As these development trends advance, the application prospects of high-resolution remote sensing ore-forming information extraction based on deep learning will become more widespread, providing more powerful tools for resource management, ore-forming prediction, and mineral resource potential evaluation.

Table 5.11 Countries with the greatest output of core papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	20	95.24	4 037	201.85	2020.6
2	Italy	2	9.52	466	233.00	2020.5
3	USA	2	9.52	69	34.50	2022.0
4	Netherlands	1	4.76	623	623.00	2019.0
5	Australia	1	4.76	61	61.00	2020.0

Table 5.12 Institutions with the greatest output of core papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Wuhan University	9	42.86	2 248	249.78	2020.1
2	Chinese Academy of Sciences	3	14.29	368	122.67	2020.7
3	Beihang University	2	9.52	795	397.50	2020.5
4	Nanjing University of Information Science and Technology	2	9.52	468	234.00	2020.0
5	China University of Mining and Technology	2	9.52	277	138.50	2020.0
6	Xinjiang University	2	9.52	253	126.50	2021.5
7	Capital Normal University	2	9.52	194	97.00	2021.5
8	University of Utrecht	1	4.76	623	623.00	2019.0
9	Collaborative Innovation Center of Geospatial Technology	1	4.76	347	347.00	2020.0
10	Italian Space Agency	1	4.76	347	347.00	2020.0

Table 5.13 Countries with the greatest output of citing papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 173	73.04	2022.1
2	USA	96	5.98	2021.8
3	India	58	3.61	2022.4
4	UK	50	3.11	2022.0
5	Germany	47	2.93	2021.8
6	Italy	42	2.62	2021.8
7	Republic of Korea	40	2.49	2021.8
8	Canada	33	2.05	2021.8
9	France	24	1.49	2021.8
10	Australia	22	1.37	2021.9

Table 5.14 Institutions with the greatest output of citing papers on “high-resolution remote sensing ore-forming information extraction based on deep learning”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Wuhan University	179	26.09	2021.9
2	Chinese Academy of Sciences	166	24.20	2022.0
3	Xidian University	55	8.02	2022.2
4	China University of Geosciences	49	7.14	2022.0
5	Nanjing University of Information Science and Technology	46	6.71	2021.8
6	Sun Yat-sen University	40	5.83	2022.0
7	Northwestern Polytechnical University	34	4.96	2021.8
8	Beihang University	31	4.52	2022.0
9	Nanjing University of Science and Technology	29	4.23	2022.1
10	Ministry of Natural Resources	29	4.23	2022.2



Figure 5.7 Collaboration network among major countries in the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

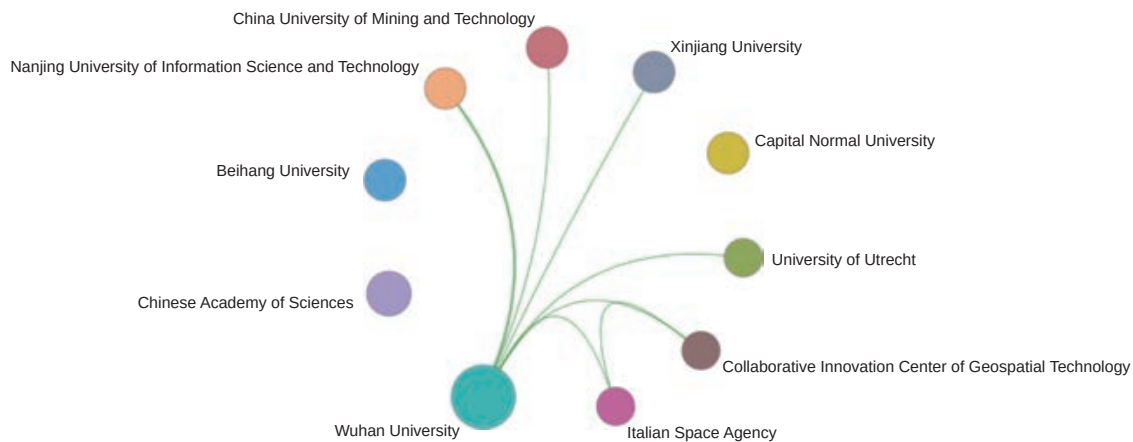


Figure 5.8 Collaboration network among major institutions in the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

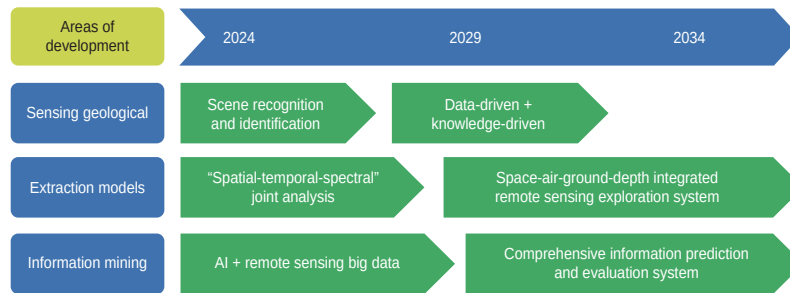


Figure 5.9 Roadmap of the engineering research front of “high-resolution remote sensing ore-forming information extraction based on deep learning”

5.1.2.4 Oil and gas with wind-light-heat-storage multi-energy integrated development and utilization

The integrated development and utilization of multiple energy sources is a key approach to building a clean, low-carbon, safe, and efficient new energy system, and is also an inevitable trend in addressing energy challenges in oil and gas exploration and development. In the context of oil and gas field development, combining new energy sources such as wind, solar energy, and geothermal energy with traditional fossil fuels enables the complementary synergy of multiple energy sources. This further promotes the steady increase and efficient development of oil and gas production, thereby advancing the sustainable development and green, low-carbon transformation of the oil and gas industry.

In the field of multi-energy integration, countries such as the USA and Japan have actively issued policies to support this development. For instance, as early as 1989, Sweden established a solar and biomass combined heating project. In recent years, the integrated development and utilization of wind-light-heat-storage, which involves the synergistic optimization of new energy and energy storage, has become a research hotspot. The research mainly focuses on systems composed of photovoltaic and wind power stations with storage batteries, or systems paired with electric heating and heat accumulation devices, aiming to optimize equipment capacity and analyze the economic performance of power generation systems. With increasing uncertainties such as energy supply shortages and unclear global economic prospects, promoting the development of wind-light-heat-storage integration in oil and gas field scenarios will provide effective means for the high-quality development of the oil and gas industry. Fully leveraging wind power development to supply green electricity to oil and gas platforms can create a complementary power supply model between wind power and regional oil and gas field power systems, enhancing the local consumption capacity of

new energy. In oil and gas mining areas and their surrounding regions, utilizing solar energy for heat collection and accumulation technology can fully harness the diverse functions of geothermal energy storage, such as peak shaving, frequency regulation, emergency backup, and capacity support, thereby promoting the application of geothermal energy in both power supply and oil and gas exploration scenarios, and advancing the coordinated development of energy storage and new energy sources. In the later stages of crude oil extraction, energy consumption per ton of oil is approximately 140–160 kW·h, with electricity expenses accounting for over 30% of development costs. The integrated development and utilization of wind-light-heat-storage can locally consume photovoltaic and wind energy at a transaction price lower than that of the State grid, optimizing oil and gas development, maximizing economic benefits, and ensuring safe and environmentally friendly operations.

The research directions for the integrated development and utilization of oil and gas with wind-light-heat-storage will focus on improving the accuracy of wind and solar resource forecasting and the precision of wind and photovoltaic power generation forecasting. It will also aim to enhance the adaptability of wind and photovoltaic power generation to power system disturbances, expand the functions of geothermal energy storage for peak shaving and frequency regulation, and support the stable operation of oil and gas production. Additionally, for oil and gas field application scenarios, optimizing system equipment configuration schemes according to local conditions will be essential to achieve the economic supply of energy through a coordinated multi-energy system. Furthermore, strategies will be developed to address real-time fluctuations in weather conditions, such as solar intensity, wind speed, and temperature, as well as energy demand, ensuring flexible and reliable energy supply. System parameter control methods will be optimized, and the distribution of electrical and thermal energy will be rationalized to achieve flexible and reliable energy supply.

In the research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”, the main contributing countries are China, the USA, and Germany (Table 5.15 and Figure 5.10). The primary contributing institutions are Chinese Academy of Sciences, Tsinghua University, and National University of Singapore (Table 5.16). There are institutional collaborations among Chinese Academy of Sciences, Tsinghua University, Swiss Federal Institute of Technology Zurich, University of Cambridge, Lawrence Berkeley National Laboratory, University of California, Berkeley, Massachusetts Institute of Technology, and Colorado School of Mines (Figure 5.11). The top three countries in terms of citing papers are China, the USA, and Australia (Table 5.17). The main output institutions of citing core papers are Chinese Academy of Sciences, Tsinghua University, Tianjin University, Zhengzhou University, and University of Science and Technology of China (Table 5.18).

Multi-energy synergy can promote the integrated development of new and traditional energy industries, serving as an important means of building a clean, low-carbon, safe, and efficient new energy system. By focusing on clean substitution, various green electricity devices can be deployed at production sites, abandoned oil and gas wells (fields), and other locations, maximizing the substitution rate of green electricity in oil and gas fields.

Table 5.15 Countries with the greatest output of core papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	121	38.78	18 982	156.88	2019.9
2	USA	57	18.27	12 905	226.40	2019.9
3	Germany	35	11.22	8 282	236.63	2019.8
4	UK	31	9.94	6 135	197.90	2019.8
5	Australia	23	7.37	6 114	265.83	2020.1
6	India	20	6.41	2 779	138.95	2020.6
7	Canada	18	5.77	3 273	181.83	2020.6
8	Saudi Arabia	16	5.13	1 729	108.06	2020.2
9	Singapore	14	4.49	3 216	229.71	2020.1
10	Italy	14	4.49	2 251	160.79	2020.1

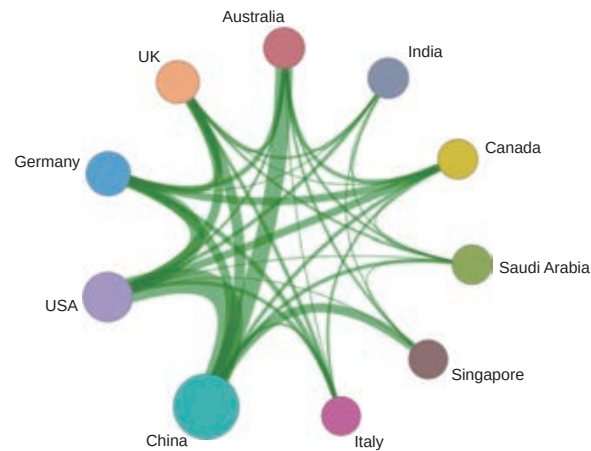


Figure 5.10 Collaboration network among major countries in the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

Table 5.16 Institutions with the greatest output of core papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	16	5.13	2 972	185.75	2020.3
2	Tsinghua University	9	2.88	1 654	183.78	2019.7
3	National University of Singapore	9	2.88	1 547	171.89	2020.1
4	Swiss Federal Institute of Technology Zurich	7	2.24	1 240	177.14	2020.9
5	Tianjin University	7	2.24	915	130.71	2019.4
6	University of Cambridge	6	1.92	1 979	329.83	2020.2
7	Lawrence Berkeley National Laboratory	6	1.92	1 063	177.17	2019.2
8	University of California, Berkeley	6	1.92	988	164.67	2019.0
9	Massachusetts Institute of Technology	6	1.92	896	149.33	2021.0
10	Colorado School of Mines	5	1.60	2 786	557.20	2019.8

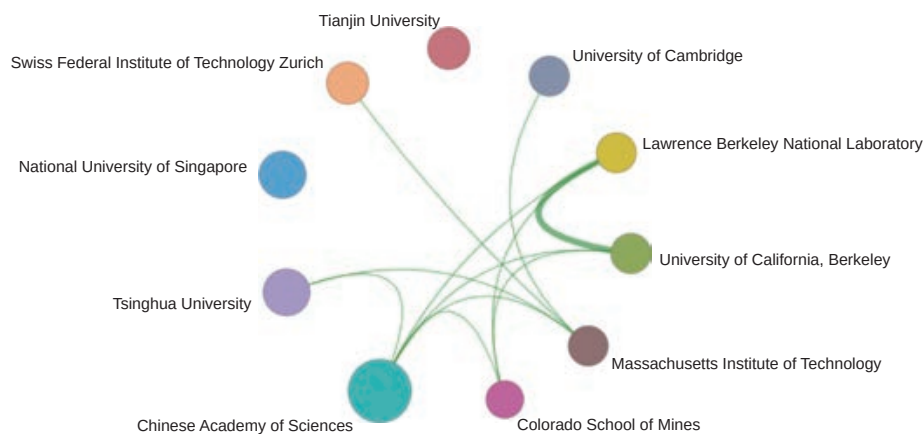


Figure 5.11 Collaboration network among major institutions in the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

Changes will also be made in production methods, process flows, and management systems, including adjustments from stable production to intermittent operations, such as intermittent pumping, injection, and gas lift. Through operational scheduling and decision-making methods, low-cost, large-scale, and high-efficiency consumption of green electricity can be achieved. The complementary adjustment capability of different types of energy storage will be expanded, reaching the coordinated optimization of electrical, thermal, and hydrogen storage, and realizing the comprehensive optimization of energy storage at oilfield sites.

The mechanisms and optimization methods of interaction between oil and gas, renewable energy (such as wind and solar), and heat accumulation within independent systems are gradually forming a synergistic mechanism and optimization method for oil and gas with wind-light-heat-storage integration. As information technology advances, the integrated development method of oil and gas with oil and gas with wind-light-heat-storage is evolving towards efficient simulation, rapid decision-making, and intelligent regulation. It is expected that by 2029, a feasibility project for the application of oil and gas with new energy will be developed, combining traditional oil and gas with new energy, and creating a diversified, wide-scale application model of energy storage technology. By 2034, collaborative optimization and control methods for multi-energy synergy in oil and gas production will be completed, forming a “low-carbon and intelligent” system for the smart extraction of new energy and oil and gas fields, geothermal energy extraction from abandoned wells, and comprehensive energy optimization, ensuring increased production and stable output of oil and gas fields, energy conservation, emission reduction, and green low-carbon practices (Figure 5.12).

Table 5.17 Countries with the greatest output of citing papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 864	46.23	2020.7
2	USA	813	13.12	2020.6
3	Australia	462	7.46	2020.8
4	UK	387	6.25	2020.9
5	India	320	5.17	2021.0
6	Germany	320	5.17	2020.6
7	Republic of Korea	270	4.36	2020.9
8	Japan	203	3.28	2020.5
9	Saudi Arabia	202	3.26	2021.1
10	Canada	179	2.89	2021.0

Table 5.18 Institutions with the greatest output of citing papers on “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	359	27.24	2020.7
2	Tsinghua University	139	10.55	2020.9
3	Tianjin University	124	9.41	2020.7
4	Zhengzhou University	103	7.81	2020.8
5	University of Science and Technology of China	101	7.66	2020.9
6	Nanyang Technological University	84	6.37	2020.6
7	The University of Queensland	84	6.37	2020.3
8	Shenzhen University	84	6.37	2020.9
9	National University of Singapore	82	6.22	2020.8
10	Zhejiang University	81	6.15	2020.8

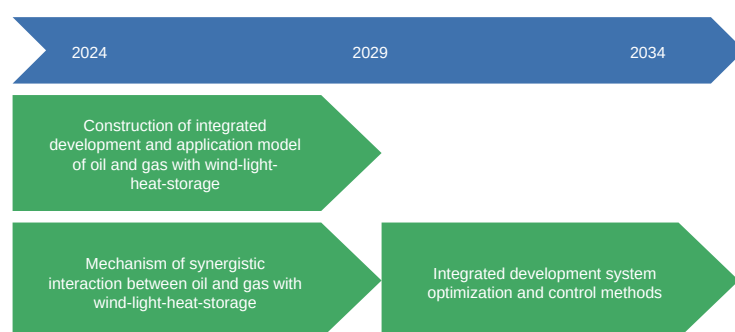


Figure 5.12 Roadmap of the engineering research front of “oil and gas with wind-light-heat-storage multi-energy integrated development and utilization”

5.2 Engineering development fronts

5.2.1 Trends in the Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 5.19. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geological resource science, technology, and engineering; and mining science, technology, and engineering. Among these 12 engineering development fronts, “high energy density, long life and low-cost solid-state battery technology”, “research and development of devices and systems of heat storage and hydrogen storage”, and “development of high-power wide-range bidirectional charging technology and equipment” represent the engineering development front of energy and electrical science; “research and development of nuclear battery based on isotope power supply”, “source searching system based on nuclear unmanned aerial vehicle”, and “nuclear reactor DCS verification and validation method, device, and system” represent the engineering development front of nuclear science, technology, and engineering; “intelligent detection and recognition system while drilling under complex geological conditions”, “technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits”, and “Real-time online prediction system for shale gas well productivity” represent the engineering development front of geological resource science, technology, and engineering; “research and development of drilling technology and equipment in deep complex strata”, “co-mining technology for coalbed methane and coal resources”, and “integrated technology of CO₂ mineralization filling and storage” represent the engineering development front of mining science, technology, and engineering. The disclosure of core patents involved in each development front from 2018 to 2023 is presented in Table 5.20.

(1) High energy density, long life, and low-cost solid-state battery technology

Solid-state batteries utilize solid-state electrolytes instead of the liquid electrolytes and separators used in traditional batteries, offering larger energy density, longer cycle life, and improved safety. Further improving the energy density of solid-state batteries increases the endurance mileage of electric vehicles, and further supports the development of electric heavy-duty trucks and electric aircraft. Specifically, solid-state batteries with an energy density of 400 W·h/kg and a stable cycle life of 2 000 cycles can increase the endurance mileage of electric vehicles to 1 000 kilometers, which is fundamental for the popularization of pure electric vehicles. In addition, the aforementioned solid-state battery can also power a two-seater light aircraft for thousands of flights, representing a key technology for emergence of the low-altitude economy. Solid-state batteries can significantly reduce the weight of aircrafts and increase their thrust-to-weight ratio, realizing the revolution of modern transportation electrification. However, the energy density and cycle life of solid-state batteries are influenced by interface instability, lithium dendrite growth,

Table 5.19 Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	High energy density, long life, and low-cost solid-state battery technology	328	648	1.98	2021.2
2	Research and development of nuclear battery based on isotope power supply	554	1 028	1.86	2020.8
3	Intelligent detection and recognition system while drilling under complex geological conditions	1 070	9 413	8.80	2020.7
4	Research and development of drilling technology and equipment in deep complex strata	199	4 026	20.23	2019.8
5	Research and development of devices and systems of heat storage and hydrogen storage	552	655	1.19	2021.9
6	Development of high-power wide-range bidirectional charging technology and equipment	812	2 078	2.56	2020.3
7	Source searching system based on nuclear unmanned aerial vehicle	638	5 917	9.27	2020.2
8	Nuclear reactor DCS verification and validation method, device, and system	203	1 199	5.91	2019.9
9	Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits	580	8 062	13.90	2020.0
10	Real-time online prediction system for shale gas well productivity	421	4 720	11.21	2020.1
11	Co-mining technology for coalbed methane and coal resources	73	1 138	15.59	2019.9
12	Integrated technology of CO ₂ mineralization filling and storage	508	1 198	2.36	2020.8

Table 5.20 Annual number of core patents published for the Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	High energy density, long life, and low-cost solid-state battery technology	28	35	39	54	85	87
2	Research and development of nuclear battery based on isotope power supply	77	84	67	97	121	108
3	Intelligent detection and recognition system while drilling under complex geological conditions	111	143	225	197	284	110
4	Research and development of drilling technology and equipment in deep complex strata	40	53	38	38	25	5
5	Research and development of devices and systems of heat storage and hydrogen storage	20	17	40	86	138	251
6	Development of high-power wide-range bidirectional charging technology and equipment	155	181	118	118	117	123
7	Source searching system based on nuclear unmanned aerial vehicle	107	124	132	114	122	39
8	Nuclear reactor DCS verification and validation method, device, and system	45	52	40	25	30	11
9	Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits	104	127	137	98	97	17
10	Real-time online prediction system for shale gas well productivity	96	91	59	61	59	55
11	Co-mining technology for coalbed methane and coal resources	16	10	23	12	11	1
12	Integrated technology of CO ₂ mineralization filling and storage	70	66	72	111	84	105

and electrolyte degradation. In addition, the synthesis process of solid-state electrolytes is complex and has a low yield. Solid-state electrolytes generally cost USD 190/kg, which is considerably higher than the commercialization threshold of USD 50/kg. Through intrinsic material modification and manufacturing process optimization, the energy density and the cycle life of solid-state batteries can be further improved, and the synthesis cost can be reduced. The modification of intrinsic materials mainly develops from the directions of positive and negative electrode material modification, electrolyte structure design, and *in situ* solid electrolyte passivation layer formation. The main development directions for electrolyte development and manufacturing process optimization are film deposition process, mass production technology, and ultrafast and precise synthesis technology. Among them, the ultrafast and precision synthesis technology can realize the precise synthesis of multi-component and even high-entropy solid-state electrolytes in just a few seconds, which can not only efficiently screen and explore electrolyte materials with specific target components, but also realize the accurate and uniform synthesis of multiple elements in single pure phase materials, which is an important trend in the future development and industrial synthesis of solid-state battery materials.

(2) Research and development of nuclear battery based on isotope power supply

Isotope power supply is a nuclear energy device that converts the decay energy into electric energy by using the static or dynamic energy conversion technology based on the heat or radiation particles generated by the decay of radioactive isotopes. Isotope power supply has advantages such as long life, high energy density, high reliability, strong environmental adaptability, self-support and maintenance-free, etc. It is an ideal choice for long-term power supply in extreme special environments, and has been applied in space exploration, deep-sea and polar exploration, and power security in extremely remote areas. The technical direction of isotope power supply mainly focuses on the research of temperature difference power supply, photovoltaic power supply, photovoltaic power supply, and dynamic Stirling power supply. Among them, the temperature difference power supply has the highest reliability and technical maturity, making it widely used; photovoltaic power supply is considered the most promising for miniaturization and integration with microelectromechanical systems (MEMSs), although its power and power density still need improvement; dynamic Stirling power supply has a high system efficiency, but issues concerning the reliability and lifespan of moving parts need to be addressed. In the future, aiming at the multi-domain spectral application needs of space, deep sea, and wireless networks, the development of isotope power supplies will focus on four aspects: the use of modular heat source structures to improve the safety and multi-task adaptability of thermal power supplies; the development of high-efficiency thermoelectric materials and devices to enhance the conversion efficiency and economy of thermoelectric power supplies; the breakthrough in the semiconductor chip design and stack integration technology to improve the power level, conversion efficiency, and power density of photovoltaic power supplies; and the optimization of the design and processes of free piston to solve the reliability and lifespan of dynamic Stirling power supplies.

(3) Intelligent detection and recognition system while drilling under complex geological conditions

The intelligent detection and recognition system while drilling is an advanced drilling technology designed for complex geological conditions, aimed at improving the accuracy of formation identification and operational efficiency during the drilling process. This system integrates various theories and technologies such as geology, control engineering, mechanical mechanics, data analysis, and intelligent algorithms. Through real-time monitoring and analysis of various parameters during the drilling process, it achieves intelligent detection and accurate identification of geological structures, formation lithology, oil and gas properties, and other characteristics.

The main technical directions include while drilling measurement, while drilling logging, while drilling acoustic logging, while drilling seismic, and other while drilling measurement technologies, as well as the use of advanced intelligent algorithms to process and analyze the collected data. Through these technologies, the system can obtain various physical parameters underground in real time, such as temperature, pressure, resistivity, acoustic velocity, etc., providing key information for formation evaluation and drilling decisions.

In the future, new technologies such as artificial intelligence, big data, and the Internet of Things will be continuously introduced to improve the speed and accuracy of data processing and enhance the intelligence level of the system. Technological innovation will

focus on improving the adaptability of the system to complex geological environments, solving problems such as low recognition accuracy, slow data transmission and processing speeds in existing technologies. In addition, with the overall development of the intelligent drilling technology, the research and application of hardware facilities such as intelligent drilling rigs, intelligent drill bits, and intelligent drill rods will further promote the improvement of intelligent detection and recognition systems while drilling.

(4) Research and development of drilling technology and equipment in deep complex strata

The research and development of drilling equipment and technology in deep complex strata at depths of over 10 000 meters refers to the development and application of a series of advanced drilling technologies and equipment to overcome extreme conditions such as high temperatures, high pressures, and complex formations, in order to achieve efficient and precise drilling goals. The scientific exploration of ultra-deep oil and gas resources is an important task in implementing the national “Four Deep” detection plan and helps in capturing the forefront of deep formation technology innovation. The “Taco-1 Well” in the Tarim Oilfield is the first well in China with a vertical depth exceeding 10 000 meters, whose drilling has overcome numerous challenges including ultra-high pressure, ultra-high temperature, and extreme loads, leading to the development of core technologies for safe and efficient drilling and completion of ultra-deep wells. The main technical directions include: ultra-deep well drilling equipment; optimization and expansion of well structures at extreme depths; efficient rock-breaking and drilling acceleration technologies; high-temperature resistant drilling and completion fluids; drilling fluid friction reduction technologies; high-temperature and high-pressure cementing technologies; and technologies for controlling and addressing complex conditions. The development trends include enhancing the integration of geological engineering to improve detection accuracy in complex geological environments; increasing the intelligence and modularity of deep formation drilling equipment for real-time diagnosis, prediction, and control; developing high-performance materials resistant to high temperatures, high pressures, and corrosion to enhance durability under extreme conditions; and innovating drilling acceleration methods and tools to improve rock-breaking efficiency.

(5) Research and development of devices and systems of heat storage and hydrogen storage

Thermochemical energy storage is a technology that stores and releases heat through reversible gas-solid chemical reactions. The reversible chemical reaction between the alloy and hydrogen is also a solid-state hydrogen storage technology. Magnesium-based metal/titanium-based metal alloys react with hydrogen to form metal hydrides for hydrogen storage and the release of heat. The hydrides are then heated and undergo decomposition reactions to release hydrogen gas. Therefore, it can be regarded as a technology that integrates thermochemical heat storage and solid-state hydrogen storage.

Current research often separates thermochemical heat storage from solid-state hydrogen storage and utilizes them separately. However, the processes of storing and releasing hydrogen are constrained by the processes of storing and releasing heat and heat transfer, which affect each other. Moreover, the magnitude of the heat of the chemical reaction has a significant impact on the energy storage efficiency of solid-state hydrogen storage. In the future, if the processes of storing and releasing hydrogen and heat are considered together to achieve combined hydrogen and heat supply, it could be an effective method to improve energy utilization efficiency.

The design optimization of devices and systems is an important challenge in this technology, which requires comprehensive consideration of factors such as high heat transfer performance, high system utilization efficiency, and reaction cycle stability for system integration. It requires collaborative consideration from multiple disciplines such as chemistry, heat transfer, thermodynamics, and mechanical design. These technologies are poised to bring new breakthroughs to the fields of hydrogen and heat storage.

(6) Development of high-power wide-range bidirectional charging technology and equipment

The high-power wide-range bidirectional charging technology refers to the bidirectional direct current (DC) /alternating current (AC) conversion between electric vehicles (EVs) and the power grid, which relies on the application of high-power bidirectional charging piles. For the high-power bidirectional charging piles, the AC input and output voltages of the power grid are commonly single-phase 220 V or three-phase 380 V, while the DC input and output voltages of EVs range from 200 V to 1 000 V, with a bidirectional power of up to 240 kW. The high-power wide-range bidirectional charging technology enhances the utilization efficiency of energy

and the flexibility and economy of EVs, which also increases the interaction between EVs and the power grid.

The main research topics in this field include: the bidirectional AC/DC and DC/DC conversion technology; the improvement of bidirectional charging power and voltage range; voltage resistance, insulation and heat dissipation technologies; the integrated management technology of bidirectional charging; the bidirectional charging metering technology; communication protocols among EVs, bidirectional charging piles and the power grid; and the optimization of bidirectional charging strategies, etc.

The research prospects include: investigating the high-efficiency high-power bidirectional AC/DC converter; improving the heat dissipation efficiency, reliability and service life of charging piles by utilizing the liquid cooling technology, which also downsizes the charging guns; and constructing the bidirectional charging energy management platform to achieve the information exchange and coordinated regulation among EVs, charging piles, and the power grid.

(7) Source searching system based on nuclear unmanned aerial vehicle

With the increasingly mature commercial use of unmanned aerial vehicles, the use of unmanned aerial vehicles equipped with radiation monitors for radiation monitoring or radioactive source search can achieve efficient search for radioactive sources in radiation accidents and reduce the risk of radiation exposure of source seekers. Unmanned aerial vehicles can be applied to nuclear accident pollution monitoring, radiation site investigation, and radioactive source search and other fields. Based on the good maneuverability of small unmanned rotorcraft, the real-time monitoring of large-scale environmental radioactivity is realized by combining nuclear detection, signal processing, GPS positioning, wireless communication and other technologies, and the data interaction between the airborne monitoring system and the ground control station is realized through the wireless data transmission module. The upper computer software obtains the measurement data in real time and processes it to display the radiation hot spot map of the current measurement environment. The core equipment and technology of the system include radiation detection equipment, which can simultaneously measure environmental dose rate and energy spectrum. For example, the source finding iterative algorithm is used to accurately locate the radioactive source. The Kriging interpolation algorithm is used to map the dose rate and outline the hot spots in the radioactive environment, which is of great significance for the search of radioactive sources and the detection for radioactive leaks.

(8) Nuclear reactor DCS verification and validation method, device, and system

Distributed control system (DCS) is a multilevel computer system composed of process control level and process monitoring level, linked by a communication network. As the central nervous system of a nuclear power plant, the distributed control system is divided into the safety-level distributed control system and the non-safety-level distributed control system. Its function is to monitor various parameters of the operation of the nuclear power plant in real time, including the protection and control of the nuclear reactor, which plays a very important role in ensuring the safe, reliable, and stable operation of the nuclear power plant. According to the requirements of HAF, the verification and validation of the safety-level distributed control system are necessary steps to ensure the security and reliability of the software. The design feature of the verification simulation platform is to adopt advanced and mature digital monitoring system configuration software with good openness, establish a simulation model that can accurately simulate the dynamic operational characteristics of the controlled system, and provide necessary real-time operational feedback for the control system to form a control closed loop. These simulation models include relevant physical reactor models, electrical models, thermal hydraulic models, and control simulation models. Through the integration of instrument control main control room human-machine interface design, logic diagram, and simulation diagram control system functions, a simulation platform can be independently designed to dynamically and real-time simulate and modify basic physical phenomena and dynamic processes of nuclear power plants according to verification requirements.

(9) Technology for identifying and locating favorable ore-forming spaces in the depth of granite-type uranium deposits

Uranium is a strategic resource for both military and civilian use, which plays a significant role in national and energy security. Granite-type uranium deposits are essential industrial uranium resources in China. However, due to the limited prospecting depth, the explored depth of granite-type uranium deposits is mostly 500 m. In recent years, the prospecting depth has reached

1 000–1 200 m, while the prospecting depth of similar uranium deposits abroad exceeds 2 000 m. The main research directions for deep favorable metallogenic space identification and positioning technology of granite-type uranium deposits include the deep favorable metallogenic space plane and vertical positioning geological tracer technology, the deep geological structure and uranium metallogenic conditions geophysical detection technology, the multi-element metallogenic information comprehensive extraction technology, the three-dimensional geological-metallogenic-exploration model construction technology, and the deep uranium resources efficient, comprehensive prediction and evaluation technology, etc. This technological system has achieved remarkable results in prospecting several granite-type uranium deposits. In the Youdong area of the uranium ore field in the southern Zhuguang region, a thick industrial ore body was successfully found at a depth of 950 meters. The deepest industrial uranium deposit in China was found at a depth of 1 550 meters, refreshing the depth record of industrial uranium deposits in China. With the development and application of prospecting and prediction technologies such as big data and artificial intelligence, the main development trends of the deep favorable metallogenic space and positioning technology of granite-type uranium deposits in the future include the element-isotope geological identification technology for deep concealed ore bodies, the enhanced extraction technology for weak anomaly information in deep areas, the high-precision geophysical detection technology, the intelligent prospecting and prediction technology for deep uranium resources based on big data, and the four-dimensional modeling and prediction and evaluation technology for large-depth granite-type uranium deposits.

(10) Real-time online prediction system for shale gas well productivity

The real-time online prediction system for shale gas well productivity is a comprehensive system that integrates data acquisition, processing, analysis, and prediction functions. The system aims to establish a quantitative evaluation model by monitoring the production data of shale gas wells in real time and to quickly and accurately predict the production capacity of shale gas wells. This real-time online prediction can improve both efficiency and accuracy, providing an important basis for shale gas development.

The main technical directions include: ① establishing a target production dataset for shale gas wells, using neural network training to obtain a dynamic production prediction model, and determining the production of shale gas wells at the target time; ② developing an integrated shale gas well production capacity evaluation model using the Markov chain Monte Carlo intelligent historical fitting algorithm and the embedded discrete fracture technology coupled with a numerical simulator to predict shale gas well production capacity, taking into account fracture modeling, dynamic simulation, historical fitting, and production capacity prediction; ③ evaluating and predicting the production of shale gas wells by integrating geological, drilling, fracturing, and production data from the entire shale gas extraction cycle, and using machine learning, taking into account both geological and engineering factors.

The future development trend is to integrate advanced technologies such as machine learning and deep learning with statistical theoretical models to improve the accuracy and efficiency of shale gas well productivity prediction, and achieve dynamic and to phased evaluation and prediction.

(11) Co-mining technology for coalbed methane and coal resources

The co-extraction technology of coal-bed methane (CBM) and coal resources has emerged as a cutting-edge approach in the field of coal mining in recent years. This technology aims to achieve the efficient, economical, and environmentally friendly joint extraction of coalbed methane and coal, thereby enhancing resource utilization, reducing environmental impact, and contributing to the transformation of the energy structure. The primary research directions include the integration of extraction technologies, assessment of coalbed methane resources, analysis of hydrogeological impacts, intelligent monitoring and control technologies, and studies on economic viability and sustainability.

In the future, the co-extraction technology of coalbed methane and coal resources is expected to evolve towards greater intelligence, greenness, and systematization. In terms of intelligence, advancements in sensor technologies and data processing capabilities will lead to the more widespread adoption of intelligent monitoring and control systems, facilitating real-time monitoring and optimization of the extraction process. Regarding greenness, technological developments will place greater emphasis on environmental protection, striving to minimize ecological impacts during coalbed methane extraction and to prevent soil erosion and groundwater contamination. From a systematic perspective, there will be a push for interdisciplinary integration,

combining research findings from geology, engineering, environmental science, and other fields to develop a comprehensive framework for co-extraction technologies, thereby optimizing the integrated development and utilization of resources.

(12) Integrated technology of CO₂ mineralization filling and storage

The integrated technology of carbon dioxide (CO₂) mineralization backfilling and storage is an organic combination of the CO₂ storage technology and the backfill mining technology, to achieve large-scale utilization and storage of CO₂. This technology immobilizes CO₂ within the cement paste backfill material through mineralization reactions. It not only effectively reduces CO₂ emissions, enhances the strength of the backfill, and lowers filling costs, but also mitigates the environmental and spatial impacts of improper solid waste disposal. Additionally, it addresses issues such as strata movement and surface subsidence caused by mining activities. The technology primarily involves three key stages preparation of carbon-sequestering cement paste backfill materials, cement paste backfill slurry transportation, and the formation of cement paste backfill strength. The process includes sub-processes like mineralization reactions, cement paste backfill slurry transportation, and the diffusion of CO₂ within the cement paste backfill material. The main research directions for this technology include: ① study of three-phase (solid-liquid-gas) pipeline transportation; ② investigation of CO₂ mineralization mechanisms; ③ research on the mechanical properties of mineralized cement paste backfill; ④ development of CO₂ mineralization enhancement techniques; ⑤ preparation techniques for CO₂ backfill materials; ⑥ study of the physical-chemical synergistic mechanisms of CO₂ sequestration; ⑦ research on CO₂ backfilling mining methods. The core objectives of the integrated technology of CO₂ mineralization backfilling and storage are to increase CO₂ sequestration capacity and reduce backfilling costs, ultimately protecting the environment while saving costs.

5.2.2 Interpretations for four key engineering development fronts

5.2.2.1 High energy density, long life, and low-cost solid-state battery technology

Solid-state batteries use solid electrolytes instead of liquid electrolytes and separators used in traditional batteries, which provide the possibility for the use of lithium metal anodes, thereby greatly enhancing the energy density of lithium-ion batteries. The high energy density is a necessity to further increase the market penetration rate of electric vehicles and promote the electrification revolution of vehicles. Recently, the key factors affecting the energy density and cycle life of solid-state batteries are the instability of the electrode-electrolyte interface, the growth of lithium dendrites, and the degradation of the electrolyte with battery cycles, which also result in battery capacity attenuation and safety problems. In addition, the complex synthesis process, low yield, and high production cost of solid-state electrolytes have become major obstacles to the commercialization of solid-state batteries.

Intrinsic material modification and manufacturing process optimization can further improve the energy density, cycle life, and reduce the synthesis cost of solid-state batteries. The modification of intrinsic materials mainly develops in the directions of positive and negative electrode material modification, electrolyte structure design, and *in situ* interface passivation layer. To alleviate the interfacial side reactions, the electrode surface is modified by coating with conductive materials, doping with Si, C, and other elements, and reducing the particle size, which increases the lithium-ion diffusion rate and improves the energy density of solid-state batteries. Optimizing the directional and continuous interface channels of ion transport in the solid electrolyte, constructing a multilayer heterogeneous electrolyte structure, and doping Zn, F, and other elements to improve the electrochemical stability of the electrolyte are conducive to reducing the growth of lithium dendrites, decreasing the degradation of the electrolyte, and increasing the cycle life of the battery. By designing the *in situ* interface passivation layer rich in lithium fluoride and lithium nitride, the internal resistance of the battery can be reduced. This passivation layer could also alleviate the electrolyte degradation and suppress dendrite growth, improving the cycle performance and safety performance of the solid-state battery. However, due to the distinct coupling characteristics of chemical fields, electric fields, and force fields in the internal and interfacial electrochemical processes of solid-state batteries, it is difficult for a single design to include all the comprehensive parameters. Considering the multi-field coupling effect, the experimental environments and theoretical models of solid-state electrolytes under real working conditions are constructed, which can effectively reveal the failure and runaway mechanisms in their practical application and provide strong support for the design of

solid-state battery energy density and optimization of cycle life.

The optimization of the manufacturing process mainly includes the improvement of the film formation process, large-scale production technology, and ultra-fast precision synthesis technology. The film-forming process is divided into the wet process and the dry process. Although the wet process is one of the most promising processes to achieve mass production of solid electrolyte membranes, it still needs further research and development. The large-scale production technology of electrolytes is still under exploration, where the high cost of raw materials and homogenized synthesis are urgent challenges that need to be overcome. The industry is expected to achieve small-scale production by 2025, while large-scale commercialization needs to wait until around 2030. The ultra-fast and precise synthesis technology can realize the ultra-fast synthesis of multi-component high-entropy solid-state electrolytes in just a few seconds, which can not only efficiently screen and explore electrolyte materials with specific target components but also realize the accurate and uniform synthesis of multiple elements in a single pure phase, which is an important trend in the future development and industrial synthesis of solid-state battery materials.

In the research front of “high energy density, long life, and low-cost solid-state battery technology”, China ranks first in the world with 149 patent disclosures, accounting for 45.43% of the number of patents published, followed by Japan, the USA, and Republic of Korea (Table 5.21). Among them, the USA has the most cooperation with Republic of Korea, while China has primarily established cooperation with the USA (Figure 5.13). The main output institutions of patent include Toyota Motor Corporation, Hyundai Motor Company, Kia Corporation, Panasonic Corporation, LG Chem Ltd., Nissan Motor Co., Ltd., Honda Motor Company, Beijing WELION New Energy Technology Co., Ltd., Samsung Electronics Co., Ltd., and BMW (Table 5.22). Among them, Hyundai Motor Company has the closest cooperation with Kia Corporation, with relatively little collaboration with other companies (Figure 5.14).

Figure 5.15 shows the roadmap of the front of “high energy density, long life, and low-cost solid-state battery technology”, which has broad development prospects in the fields of transportation electrification and energy storage systems. In the next 5–10 years, the key development directions of this field are the improvement of intrinsic material properties and large-scale manufacturing processes. Based on the modification of positive and negative electrode materials, electrolyte structure design, and *in situ* interface passivation layers, the energy density and cycle life of solid-state batteries could be further improved, with the realization of battery miniaturization and portability. Meanwhile, the large-scale mass production technology of electrolytes, the optimization of the film-forming process, and ultra-fast and precise synthesis technology are candidate methods to enhance the mass production process of solid-state batteries. These methods could also support the fields of energy and power by improving social and economic benefits.

Table 5.21 Countries with the greatest output of core patents on “high energy density, long life, and low-cost solid-state battery technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	149	45.43	200	30.86	1.34
2	Japan	61	18.60	220	33.95	3.61
3	USA	45	13.72	99	15.28	2.20
4	Republic of Korea	43	13.11	65	10.03	1.51
5	Germany	17	5.18	21	3.24	1.24
6	Belgium	5	1.52	14	2.16	2.80
7	UK	4	1.22	15	2.31	3.75
8	France	3	0.91	0	0.00	0.00
9	Netherlands	2	0.61	11	1.70	5.50
10	Spain	2	0.61	10	1.54	5.00

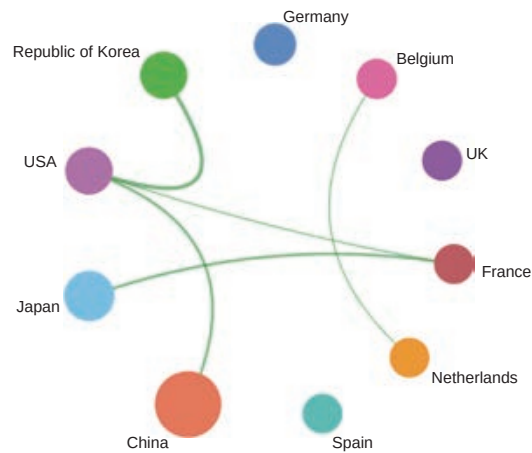


Figure 5.13 Collaboration network among major countries in the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

Table 5.22 Institutions with the greatest output of core patents on “high energy density, long life, and low-cost solid-state battery technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Toyota Motor Corporation	17	5.18	41	6.33	2.41
2	Hyundai Motor Company	15	4.57	47	7.25	3.13
3	Kia Corporation	14	4.27	33	5.09	2.36
4	Panasonic Corporation	11	3.35	76	11.73	6.91
5	LG Chem Ltd.	9	2.74	6	0.93	0.67
6	Nissan Motor Co., Ltd.	8	2.44	0	0.00	0.00
7	Honda Motor Company	7	2.13	17	2.62	2.43
8	Beijing WELION New Energy Technology Co., Ltd.	7	2.13	2	0.31	0.29
9	Samsung Electronics Co., Ltd.	7	2.13	1	0.15	0.14
10	BMW	6	1.83	10	1.54	1.67

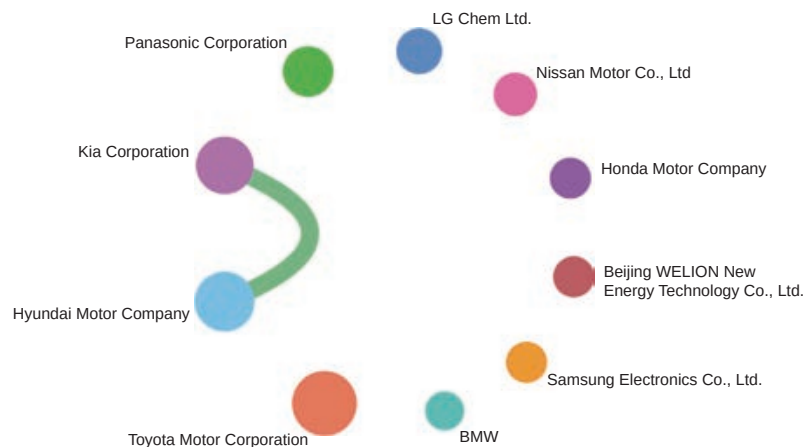


Figure 5.14 Collaboration network among major institutions in the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

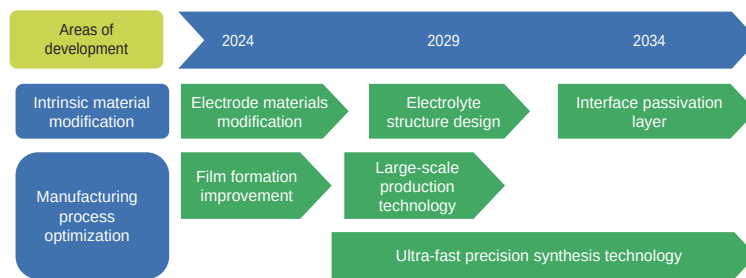


Figure 5.15 Roadmap of the engineering development front of “high energy density, long life, and low-cost solid-state battery technology”

5.2.2.2 Research and development of nuclear battery based on isotope power supply

Compared with chemical and solar cells, isotope power supply has the advantages of high energy density, strong environmental adaptability, and self-sustainability without maintenance. It is the most promising power supply technology for space exploration, deep-sea and polar exploration, and wireless networks. Since its first application in 1961, the isotope power supply has been regarded as a disruptive technology by developed countries such as the USA, Russia, and the United Kingdom. For different application environments such as space, land, and underwater, a series and spectral temperature difference isotope power supply products have been developed in the last century. Notable examples include the “SNAP”, “HWM-RTG”, “GPHS-RTG”, and “MMRTG” plutonium-238 thermoelectric power supplies for space exploration in the USA, the “Penguin”, “Beta-M”, and “Senostav” strontium-90 thermoelectric power supplies for far-sea and polar weather monitoring and navigation in Russia, and the “RIPPLE” strontium-90 thermoelectric power supply for navigation beacons in the United Kingdom, with power coverages ranging from watts to hundreds of watts and efficiency increasing from 2% to 6.7%. In order to meet the power needs of deep space and deep-sea exploration in the new century, the USA has accelerated the development of next-generation isotope power sources, including structural optimization and improvement of modular heat sources (GPHS) to improve the safety of space applications; development of high temperature and high ZT value thermoelectric materials such as cobaltite, semi-Ha, and germanium silicon to improve the efficiency of the power system; development of efficient insulation structure and high emissivity coating to improve the thermal efficiency of the system; and the research, development, and testing of dynamic Stirling conversion power supplies. At the same time, for future wireless sensing network and MESM system integrated power supplies, both the USA and Russia have proposed research and development plans for micro tritium and nickel-63-volt power supplies.

At present, China, the USA, Japan, Russia, and Republic of Korea are the main forces in the international research and development of isotope power supplies (Table 5.23). Among them, China has developed rapidly in the past 10 years, and realized space applications in 2018, ranking first in the number of patents disclosed. The USA, which started the earliest and developed the most comprehensively, has the highest level of technology and maturity, ranking second in the number of patents disclosed. Russia has been slower due to its economic situation, ranking fourth in the number of patents disclosed. Due to its relevance to national strategic core technologies, countries follow the principle of independent development in the field of isotope power supply technology, and there are no reports of cooperation. The research and development of isotope power supply in China is mainly conducted by the China Institute of Atomic Energy (Table 5.24), and there are currently no reports of cooperation.

In the next 10 years, according to the needs of different scenarios, the development of isotope power supplies will continue to improve the power level, conversion efficiency, power density, and safety of the power supply as the focus of technological breakthroughs, and gradually improve the multi-task adaptability of isotope power supplies through modularization and standardization, thereby expanding their application range. Figure 5.16 shows the roadmap of the engineering development front of “research and development of nuclear battery based on isotope power supply”.

Table 5.23 Countries with the greatest output of core patents on “research and development of nuclear battery based on isotope power supply”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	471	85.02	873	84.92	1.85
2	USA	30	5.42	90	8.75	3.00
3	Japan	19	3.43	30	2.92	1.58
4	Russia	9	1.62	2	0.19	0.22
5	Republic of Korea	6	1.08	5	0.49	0.83
6	UK	3	0.54	15	1.46	5.00
7	Italy	3	0.54	7	0.68	2.33
8	France	2	0.36	0	0.00	0.00
9	India	2	0.36	0	0.00	0.00
10	Turkey	2	0.36	0	0.00	0.00

Table 5.24 Institutions with the greatest output of core patents on “research and development of nuclear battery based on isotope power supply”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Institute of Atomic Energy	27	4.87	78	7.59	2.89
2	Xi'an Jiaotong University	12	2.17	82	7.98	6.83
3	Jilin University	10	1.81	19	1.85	1.90
4	Zhejiang University	7	1.26	4	0.39	0.57
5	Shandong Qilu Stem Cell Engineering Co., Ltd.	6	1.08	21	2.04	3.50
6	Yinfeng Biological Group Co., Ltd.	6	1.08	4	0.39	0.67
7	East China University of Technology	6	1.08	0	0.00	0.00
8	Anhui Guyi Biotechnology Co., Ltd.	5	0.90	15	1.46	3.00
9	Nanjing University of Aeronautics and Astronautics	5	0.90	13	1.26	2.60
10	Mitra RxDx, Inc.	5	0.90	7	0.68	1.40

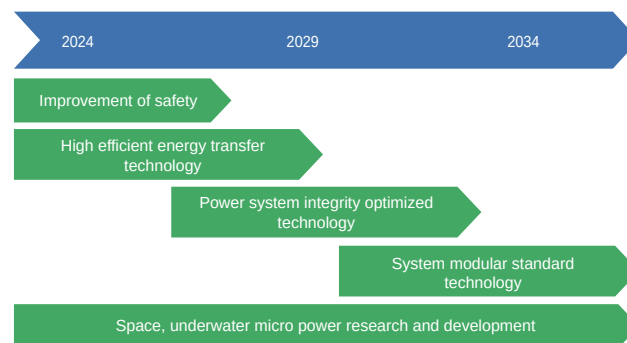


Figure 5.16 Roadmap of the engineering development front of “research and development of nuclear battery based on isotope power supply”

5.2.2.3 Intelligent detection and recognition system while drilling under complex geological conditions

The development of an intelligent detection and recognition system while drilling under complex geological conditions is a key technology in the exploration of underground resources such as oil, minerals, and coal. Especially in complex geological conditions where resource distribution is complex, this system can enhance exploration efficiency and accuracy, reduce drilling risks, and optimize development plans, which is of great significance for the exploration and development of underground resources.

The preliminary development of measurement while drilling (MWD) and logging while drilling (LWD) technologies can be traced back to the 1930s. The earliest LWD methods were based on electrical logging techniques, relying primarily on traditional measurement methods such as electromagnetic waves and acoustic waves. These systems had slow data transmission speeds and poor real-time performance. With the advancement of remote sensing instruments, various LWD technologies, such as acoustic logging and radioactive logging, have gradually developed. Progress in electronic and data processing technologies also significantly enhanced MWD and LWD techniques. After entering the 21st century, MWD systems that integrate wireless communication and high-precision sensors have become increasingly mature, providing more real-time and accurate geological data. In recent years, the rise of big data and machine learning has further propelled the development of intelligent drilling detection and identification systems. In complex geological conditions, machine learning algorithms have been employed to automatically identify geological features and optimize drilling paths. Although research and application in this field are still in their early stages, they have already demonstrated tremendous potential.

In the research front of “intelligent while-drilling detection and identification systems under complex geological conditions”, China ranks first in patent output, with 1 032 published patents, accounting for 96.45% of the total. Other countries have a share of less than 4%. The USA ranks second with 11 published patents, accounting for only 1.03% (Table 5.25). In terms of the main output institutions of patents in this field (Table 5.26), the top ten institutions are from China, among which China Railway Tunnel Group Co., Ltd., Shandong University, and China State Railway Group Co., Ltd. rank in the top three. There is international cooperation primarily among the USA, France, and Canada (Figure 5.17) in this field. There is institutional cooperation among Chinese entities, including China Railway Tunnel Group Co., Ltd., China State Railway Group Co., Ltd., and Dalian University of Technology (Figure 5.18).

In the next 5 to 10 years, the development of “intelligent detection and recognition system while drilling under complex geological conditions” will primarily focus on two areas (Figure 5.19):

1) Innovation in sensing technology: This will involve adopting new data transmission technologies, such as wired drill pipes, to ensure efficient well-to-surface data transmission in deep and ultra-deep wells. Additionally, the use of intelligent directional

Table 5.25 Countries with the greatest output of core patents on “intelligent detection and recognition system while drilling under complex geological conditions”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	1 032	96.45	8 688	92.30	8.42
2	USA	11	1.03	274	2.91	24.91
3	Japan	9	0.84	113	1.20	12.56
4	Republic of Korea	9	0.84	104	1.10	11.56
5	Canada	3	0.28	85	0.90	28.33
6	Australia	1	0.09	73	0.78	73.00
7	Iran	1	0.09	39	0.41	39.00
8	France	1	0.09	30	0.32	30.00
9	Netherlands	1	0.09	30	0.32	30.00
10	Sweden	1	0.09	19	0.20	19.00

Table 5.26 Institutions with the greatest output of core patents on “intelligent detection and recognition system while drilling under complex geological conditions”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Railway Tunnel Group Co., Ltd.	21	1.96	137	1.46	6.52
2	Shandong University	18	1.68	137	1.46	7.61
3	China State Railway Group Co., Ltd.	17	1.59	65	0.69	3.82
4	China University of Mining and Technology-Beijing	11	1.03	69	0.73	6.27
5	Shenzhen Autel Technology Co., Ltd.	7	0.65	213	2.26	30.43
6	Shandong University of Science and Technology	7	0.65	161	1.71	23.00
7	Dalian University of Technology	7	0.65	59	0.63	8.43
8	China University of Geosciences (Wuhan)	7	0.65	56	0.59	8.00
9	China Petroleum and Chemical Corporation	6	0.56	87	0.92	14.50
10	AECC South Industry Co., Ltd.	6	0.56	68	0.72	11.33

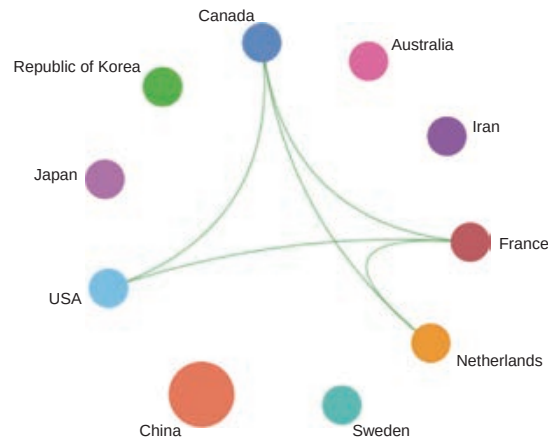


Figure 5.17 Collaboration network among major countries in the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

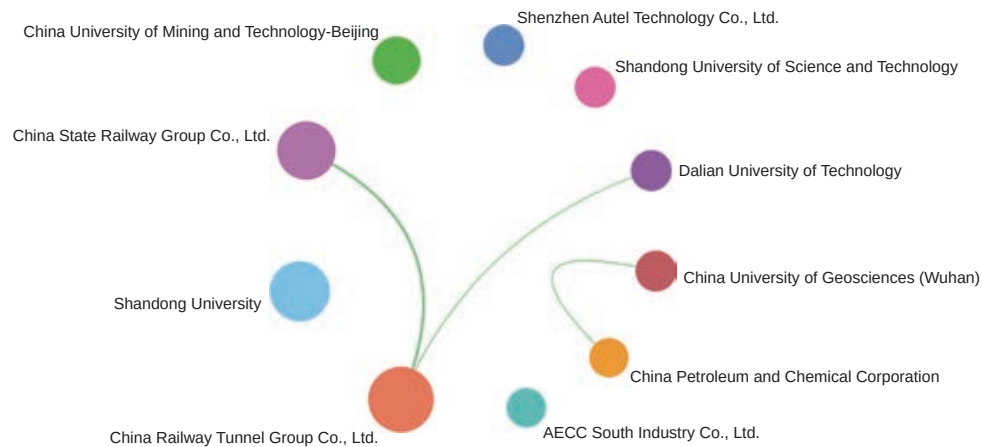


Figure 5.18 Collaboration network among major institutions in the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

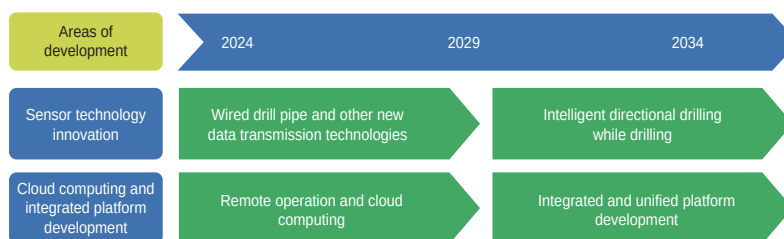


Figure 5.19 Roadmap of the engineering development front of “intelligent detection and recognition system while drilling under complex geological conditions”

drilling methods and artificial intelligence will be emphasized to enhance the level of drilling automation, enabling the system to make autonomous decisions and reducing reliance on data transmission and human experts.

2) Development of cloud computing and integrated platforms: With the advancement of the Internet of Things (IoT) and cloud computing, future intelligent while-drilling systems will enable remote operations and data processing. These systems will integrate geological data, drilling engineering, real-time monitoring, and intelligent identification to form a unified platform, simplifying drilling operations and increasing efficiency. All critical data and decision-support functions will be consolidated into a single interface, making the drilling process more streamlined and effective.

5.2.2.4 Research and development of drilling technology and equipment in deep complex strata

The research and development of drilling technology and equipment in deep complex strata at depths of over 10 000 meters is a highly challenging field of engineering technology, aimed at addressing the intricate geological environments found deep within the Earth’s crust. By developing and deploying a suite of cutting-edge drilling technologies and equipment, this endeavor aims to effectively overcome extreme conditions such as high temperatures, high pressures, and complex geological formations, thereby achieving efficient and precise drilling objectives.

The research and development of drilling technology and equipment in deep complex strata holds significant strategic importance across multiple dimensions, including resource extraction, technological innovation, and national energy security. The deep subsurface contains abundant reserves of hydrocarbons, minerals, and geothermal resources. It is estimated that 60% of the world’s newly discovered oil and gas reserves originate from deep formations. In China, 83% of deep oil and gas resources remain to be explored and developed. The development of ultra-deep drilling technology is crucial for mitigating China’s oil and gas resource shortages and ensuring the security and stability of China’s energy supply. Moreover, breakthroughs in this field will provide extensive research and application opportunities for the development of high-strength, high-temperature-resistant drilling materials and intelligent drilling systems.

In 2016, Xi Jinping, General Secretary of the Chinese Communist Party, proposed the strategic objective of “marching deep into the depth of the earth.” On May 30, 2023, the Tahe-1 well, with a planned depth of 11 100 meters, commenced drilling, tasked with the dual objectives of exploring geological structures and discovering hydrocarbon resources. In recent years, China has made significant strides in deep-earth resource exploration, consistently setting new depth records and demonstrating its strong capabilities in this arena. For instance, in the Tarim Oilfield, over 1 700 wells have been drilled to depths exceeding 6 000 meters, accounting for 80% of the total in China. On March 4, 2024, China National Petroleum Corporation (CNPC) drilled the Tahe-1 well in the heart of the Taklamakan Desert to a depth exceeding 10 000 meters, making it the deepest vertical well in Asia and further consolidating China’s leadership in ultra-deep drilling technology. At present, China has successfully developed a series of ultra-deep automated drilling rigs capable of operating at depths between 7 000 and 12 000 meters, as well as four-column rigs for 8 000 to 9 000-meter depths, which have demonstrated significant efficacy in practical applications. Additionally, the 52 MPa high-pressure drilling pump technology has matured and been widely deployed, while the development of the 70 MPa ultra-high-pressure drilling pump has also achieved success. Furthermore, prototype development or software development has

been completed in areas such as energy storage and energy management technology, drilling rig integrated control technology, intelligent decision-making and support technology, and low-pressure drilling fluid automation processing technology, and has entered the stage of industrial testing or small-scale application. The development of these technologies and equipment provides strong support for the sustainable development of deep well drilling technology in China.

In the research front of “research and development of drilling technology and equipment in deep complex strata”, China and the USA are leading in the number of core patents published, with 122 and 54 patents respectively, accounting for 61.31% and 27.14% of the total. Other countries have published less than 6.00% of the related patents. China has the highest number of cited patents, accounting for 53.35% of total citations, while the USA accounts for 34.97%, and other countries have citation ratios of less than 7.00%. Australia has the highest citations per patent (Table 5.27). In terms of patent-producing institutions (Table 5.28), ExxonMobil Upstream Research Company, China University of Petroleum-Beijing, China Petroleum and Chemical Corporation, Southwest Petroleum University, Schlumberger Technology Corporation, and PetroChina Co., Ltd. are the leading contributors. Among them, institutions with citation rates exceeding 5.00% include ExxonMobil Upstream Research Company and Sinopec (Table

Table 5.27 Countries with the greatest output of core patents on “research and development of drilling technology and equipment in deep complex strata”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	122	61.31	2 148	53.35	17.61
2	USA	54	27.14	1 408	34.97	26.07
3	France	10	5.03	264	6.56	26.40
4	Saudi Arabia	8	4.02	108	2.68	13.50
5	Canada	7	3.52	194	4.82	27.71
6	Netherlands	7	3.52	194	4.82	27.71
7	Japan	5	2.51	93	2.31	18.60
8	Republic of Korea	4	2.01	48	1.19	12.00
9	Australia	3	1.51	84	2.09	28.00
10	Norway	2	1.01	55	1.37	27.50

Table 5.28 Institutions with the greatest output of core patents on “research and development of drilling technology and equipment in deep complex strata”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	ExxonMobil Upstream Research Company	19	9.55	518	12.87	27.26
2	China University of Petroleum-Beijing	12	6.03	277	6.08	23.08
3	China Petroleum and Chemical Corporation	10	5.03	206	5.12	20.60
4	Southwest Petroleum University	9	4.52	201	4.99	22.33
5	Schlumberger Technology Corporation	7	3.52	194	4.82	27.71
6	PetroChina Co., Ltd.	7	3.52	193	4.79	27.57
7	Halliburton Energy Services Incorporation	7	3.52	157	3.90	22.43
8	Gree Electric Appliances Incorporation of Zhuhai	7	3.52	112	2.78	16.00
9	Saudi Arabian Oil Company	7	3.52	90	2.24	12.86
10	University of Electronic Science and Technology of China	4	2.01	78	1.94	19.50

2.2.8). Countries with strong collaborative efforts in this domain include China, the USA, Saudi Arabia, the Netherlands, Canada, and France (Figure 5.20). There are institutional collaborations among PetroChina Co., Ltd., China Petroleum and Chemical Corporation, and China University of Petroleum-Beijing (Figure 5.21).

The research and development of drilling technology and equipment in deep complex strata is rapidly evolving toward diversification and intelligent systems to meet the escalating challenges of deep drilling. Over the next 5 to 10 years, the level of intelligence and modularity in deep drilling equipment is expected to significantly improve, with broader applications of real-time diagnostics, predictive analytics, and control technologies to effectively manage extreme geological challenges. Concurrently, to cope with the high-pressure and high-temperature environments of deep formations, the development and deployment of high-strength, high-temperature-resistant downhole power tools, measurement-while-drilling (MWD) systems, and vertical drilling systems will be a focal point. Furthermore, the research and development of drilling materials capable of withstanding high temperatures, pressures, and corrosion will be central, as their application will markedly enhance the durability and stability of equipment in extreme environments. Additionally, to improve drilling efficiency, the innovation of drilling acceleration methods and tools will continue to advance, thereby expediting rock-breaking processes and reducing overall drilling costs (Figure 5.22).

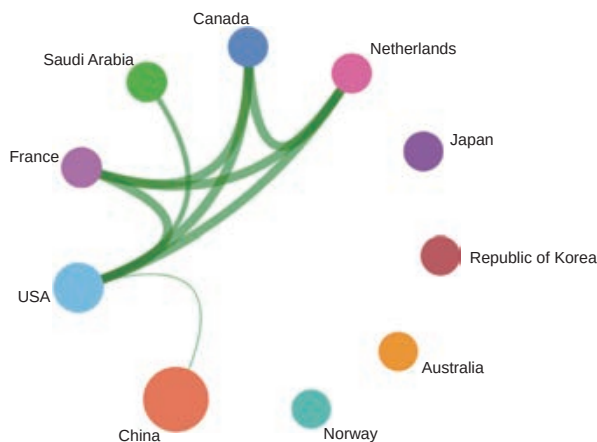


Figure 5.20 Collaboration network among major countries in the engineering development front of "research and development of drilling technology and equipment in deep complex strata"

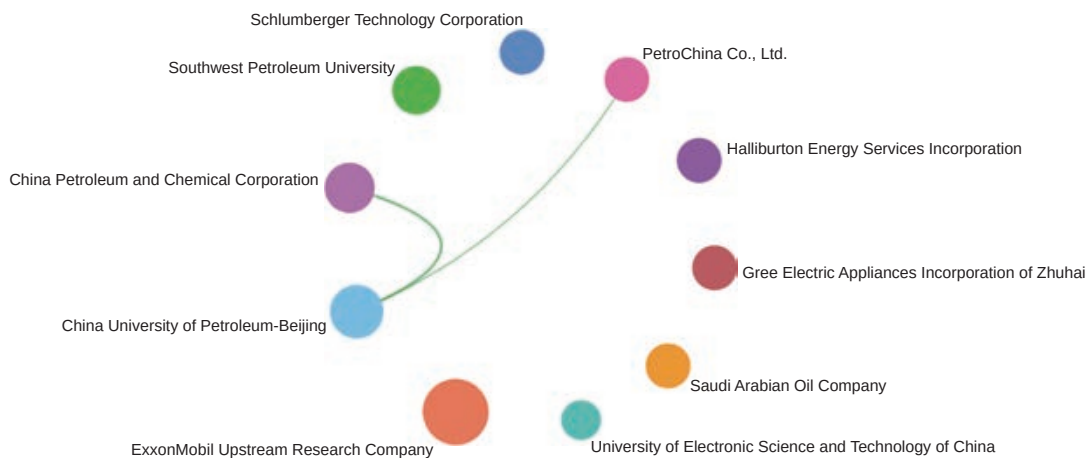


Figure 5.21 Collaboration network among major institutions in the engineering development front of "research and development of drilling technology and equipment in deep complex strata"

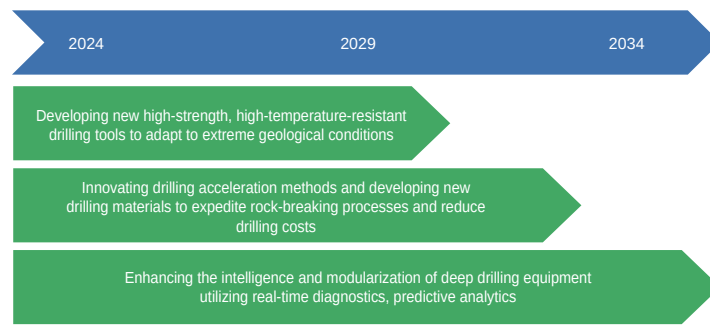


Figure 5.22 Roadmap of the engineering development front of "research and development of drilling technology and equipment in deep complex strata"

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Chapter 6 Civil, Hydraulic, and Architectural Engineering Fronts



6.1 Engineering research fronts

6.1.1 Trends in the Top 10 engineering research fronts

The Top 10 engineering research fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 6.1. These fronts cover various disciplines, including geotechnical engineering, transportation engineering, architectural design and theory, surveying and mapping engineering, urban planning and landscaping, hydraulic engineering, structural engineering, municipal engineering, and engineering mechanics. Five of them were from expert nomination: “intelligent operation and safety assurance of new energy transportation systems”, “hybrid computational paradigm for intelligent mapping”, “mechanisms and control of dynamic disaster of long tunnel in extreme environments”, “intelligent design theory for green and low-carbon engineering structures”, and “mechanisms and optimization of built environment health impacts in urban communities”. The other five fronts were identified using the co-citation clustering method applied to the top 10% of the highly cited papers, and they were confirmed in expert panel meetings. Table 6.2 presents the annual statistics of the core papers published between 2018 and 2023 that are relevant to the top ten research fronts.

(1) Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment

Extreme flood and drought disasters in river basins in changing environments refer to abnormal floods or droughts caused by the combined effects of climate change, human activities, and ecosystem changes that result in severe social, economic, and ecological losses. The occurrence and evolution of such disasters are influenced by multiple factors such as precipitation patterns,

Table 6.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment	151	7 236	47.92	2020.8
2	Urban planning and architectural design methods empowered by large models	169	8 670	51.30	2021.4
3	Intelligent operation and safety assurance of new energy transportation systems	335	21 779	65.01	2020.6
4	Physics-informed neural networks for solving engineering mechanics problems and applications	204	13 055	64.00	2022.0
5	Hybrid computational paradigm for intelligent mapping	111	4 819	43.41	2021.2
6	Low carbonization and properties optimization of ultra-high performance concrete	24	986	41.08	2022.2
7	Mechanisms and control of dynamic disaster of long tunnel in extreme environments	48	1 812	37.75	2021.5
8	Advanced oxidation/reduction technology for removing organic pollutants from water	473	43 325	91.60	2021.2
9	Intelligent design theory for green and low-carbon engineering structures	200	7 300	36.50	2021.3
10	Mechanisms and optimization of built environment health impacts in urban communities	195	9 517	48.81	2020.4

Table 6.2 Annual number of core papers published for the Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment	19	14	30	34	21	33
2	Urban planning and architectural design methods empowered by large models	9	13	24	27	47	49
3	Intelligent operation and safety assurance of new energy transportation systems	50	51	50	66	55	63
4	Physics-informed neural networks for solving engineering mechanics problems and applications	0	1	19	40	56	88
5	Hybrid computational paradigm for intelligent mapping	8	7	19	19	34	24
6	Low carbonization and properties optimization of ultra-high performance concrete	0	1	0	5	4	14
7	Mechanisms and control of dynamic disaster of long tunnel in extreme environments	2	6	6	3	15	16
8	Advanced oxidation/reduction technology for removing organic pollutants from water	0	68	81	115	103	106
9	Intelligent design theory for green and low-carbon engineering structures	12	24	25	31	47	61
10	Mechanisms and optimization of built environment health impacts in urban communities	32	39	32	29	35	28

land use, and urbanization, which exhibit significant uncertainty and complexity. In recent years, extreme flood and drought disasters, represented by major events, such as the “7 · 20” heavy rainfall and flooding in Zhengzhou, China, and the 2022 drought across the entire Yangtze River Basin, have posed significant threats to regional public safety. Therefore, studying the mechanisms underlying extreme flood and drought disasters and risk regulation in river basins is of great significance. The main research directions include: ① multi-source flood and drought disaster monitoring and data assimilation based on the integration of “space-sky-ground”; ② identification and evolution mechanisms of extreme flood and drought events in river basins under changing environment; ③ threshold values and tipping (explosion) point predictions for extreme flood and drought disasters in river basins; ④ risk assessment and regulation technologies for sudden disasters such as flash floods, flash droughts, and rapid transitions between drought and flood in river basins; ⑤ risk assessment and regulation systems for flood disasters in large and medium/large-sized cities. The future development trend lies in clarifying the nonlinear driving-response mechanisms of environmental changes and flood and drought disasters in river basins, and developing large disaster risk models driven by coupled mechanisms and data. On this basis, multi-source information can be integrated to predict and prevent various types of flood and drought disasters in river basins while accelerating the construction of a comprehensive river basin regulation system based on the “point-line-area-system” integration of cities, rivers, lakes, and water networks. A total of 151 core papers relevant to this research front were published between 2018 and 2023. These papers received 7 236 citations, with an average of 47.92 citations per paper.

(2) Urban planning and architectural design methods empowered by large models

The intersection of artificial intelligence (AI), urban planning, and architectural design has become an emerging hot spot in the industry in recent years, making targeted breakthroughs in effectiveness evaluation and design generation; however, the existing progress is mostly limited to a specific scenario. The inherent characteristics of multi-modal information enhancement, knowledge traction, and data driving the large model can effectively integrate the unique graphic and text-mixed knowledge of architectural disciplines to construct a holographic knowledge landscape. Simultaneously, large model optimization technology can provide full-link and full-intelligence transformation support in many key links of planning and architectural design, such as

current situation research and judgment, design generation, and efficiency evaluation. The frontier research directions are mainly reflected in the following aspects: ① construction of holographic knowledge map of disciplines; ② intelligent present status judgment; ③ generative planning and design; ④ efficiency evaluation of digital intelligent design. Therefore, strengthening the development and application of large model-enabled urban planning and architectural design methods in China is of positive and far-reaching significance for promoting the planning and architectural discipline based on experience, leading to a new paradigm of design science. Between 2018 and 2023, 169 core papers relevant to this research front were identified. These papers received 8 670 citations, with an average of 51.30 citations per paper.

(3) Intelligent operation and safety assurance of new energy transportation systems

The new energy transportation system refers to the application of renewable energy and advanced technologies in the field of transportation to reduce reliance on traditional fossil fuels and achieve low-carbon, environmentally friendly, and sustainable development goals. Currently, a new energy transportation system characterized by the high integration of “vehicle-energy-road-cloud” is emerging, aiming to build an intelligent, low-carbon, safe, and efficient operational and assurance system for the transportation system. This has significant implications for enhancing the autonomous controllability and green development level of the entire industry chain, as well as promoting the deep integration of transportation infrastructure with service, energy, and information networks. The main research directions include: ① heterogeneous transportation demand and multi-type clean energy supply forecasting; ② multi-objective scheduling of green smart mobility systems; ③ energy “source-grid-storage” coupling technologies responsive to transportation demand; ④ operation and maintenance of new energy infrastructure and emergency safety assurance for transportation systems. Future development trends should focus on empowering people, vehicles, roads, grids, networks, loads, storage, charging piles, and carbon emissions through intelligent and digital means; achieving efficient regulation and precise matching between transportation supply and demand, energy generation and consumption, and road construction and maintenance; and significantly enhancing the intelligent operation and safety assurance capabilities of new energy-enabled transportation systems. Between 2018 and 2023, 335 core papers relevant to this research front were identified. These papers received 21 779 citations, with an average of 65.01 citations per paper.

(4) Physics-informed neural networks for solving engineering mechanics problems and applications

Physics-informed neural network (PINN) is a type of neural network that can solve supervised learning tasks by embedding physics equations into the loss functions. This enables the neural networks to comply with any physical information described by nonlinear partial differential equations. Therefore, PINN can exhibit better generalization capabilities and stronger applicability under conditions of limited data or high noise, showing potential in solving high-dimensional differential equations for analyzing engineering structural and fluid mechanics problems, as well as in solving multi-physics coupling equations. PINNs mainly consist of two approaches: ① based on partial differential equations; ② based on energy principles. They have been widely applied to solve fluid mechanics problems, and they are primarily used in solid mechanics to address issues such as elastoplastic mechanics, fatigue and fracture problems, thermodynamic analysis, and structural dynamic response analysis. However, PINN is still disadvantageous in terms of accuracy and speed in high-order automatic differentiation numerical solutions. Dealing with complex boundary conditions is challenging. In the future, it will be necessary to further enhance the generalization capabilities of PINNs and improve their performance when facing more complex physical phenomena, which will aid in developing efficient computational tools for analyzing complex engineering mechanics problems. Between 2018 and 2023, 204 core papers related to this research topic were published. These papers received 13 055 citations, with an average of 64.00 citations per paper.

(5) Hybrid computational paradigm for intelligent mapping

Intelligent mapping is the deep fusion of new-generation AI technology with mapping technology to form new theories and methodology systems to enhance the intelligence level of key mapping technologies, such as spatial and temporal sensing, cognition, representation, and service, to aid us in solving unsolved problems, improving accuracy and efficiency, reducing costs, and/or achieving high-level services. To realize an organic integration of machine intelligence and natural intelligence in mapping, it is necessary to grasp the key factors—spatiotemporal characteristics, examine complementary advantages and

coupling mechanisms of natural intelligence in mapping and machine intelligence, reveal the roles and interrelationships of four factors, namely knowledge (K), data (D), algorithm (A), and service (S), and develop a spatiotemporal hybrid computing theory and methodology, which are guided by knowledge, driven by data, based on algorithms, and supported by services, to form an intelligent computing model KDAS that considers spatiotemporal characteristics. The main content includes ① the construction of a spatiotemporal hybrid computational paradigm, ② spatiotemporal perception computation, ③ spatiotemporal cognition computation, ④ situationalized map representation computation, and ⑤ autonomous service computation. Through research on hybrid intelligent computing for intelligent mapping, the basic paradigm of spatiotemporal hybrid intelligent computing will be developed, and a complete set of methods will be developed for real-time spatiotemporal perception, dynamic spatiotemporal cognition, situationalized spatiotemporal representation, autonomous spatiotemporal services, and other hybrid intelligent computing. This will aid in creating a theoretical and methodological system of hybrid intelligent computing for mapping and providing new methods and means for research in scientific fields, including earth science and engineering science, to drive the development of international research in this field. A total of 111 core papers relevant to this research front were published between 2018 and 2023. These papers received 4 819 citations, with an average of 43.41 citations per paper.

(6) Low carbonization and properties optimization of ultra-high performance concrete

Ultra-high performance concrete (UHPC) is an advanced civil engineering material characterized by ultra-high strength, superior ductility, and excellent durability, showing great potential for applications in fields such as bridges and railway infrastructure, marine engineering, and structural reinforcement. Nevertheless, the preparation process of conventional UHPC involves the extensive use of energy-intensive materials, such as cement and silica fume, resulting in low environmental and economic efficiency. Additionally, as the strength of UHPC continues to improve through optimization, its ductility tends to decrease, making it challenging to satisfy the demands of engineering structures in various severe environments. Therefore, research on achieving low-carbon UHPC across its entire life cycle and the design of UHPC materials that balance strength and ductility is of significant importance. Specific research directions include: ① mix design methods for UHPC based on construction and industrial waste resources; ② low-energy UHPC preparation technologies; ③ synergistic enhancement mechanisms for improving the strength and ductility of UHPC; ④ properties optimization technologies for UHPC in complex and harsh environments. Future development trends in this area will focus on addressing the challenges of high carbon emissions over the UHPC life cycle and the difficulty in balancing strength and ductility. Further research will be conducted to reduce the carbon footprint of UHPC by considering its key life cycle stages, including raw material production, mix design, and structural maintenance. On this basis, multiscale research methods will be employed to achieve simultaneous improvements in strength, ductility, and durability of UHPC in severe environments, promoting the application of low-carbon high-performance concrete materials and supporting the green transformation of the construction industry. Twenty-four core papers relevant to this research front were published between 2018 and 2023. These studies received 986 citations, with an average of 41.08 citations per paper.

(7) Mechanisms and control of dynamic disaster of long tunnel in extreme environments

Extreme environments in long tunnels refer to the challenging conditions encountered during their construction and operation of long tunnels, such as intense tectonic zones, high *in situ* stress, high geotemperature, and high seismic intensity. These extreme environments give rise to dynamic hazards, such as strong earthquakes, active fault displacements, and rockbursts, all of which pose significant threats to the safety of tunnel construction and operation. Moreover, the occurrence of such dynamic hazards is characterized by uncertainty and multi-hazard coupling, leading to complex disaster-forming mechanisms. In recent years, the construction of long tunnels in high-stress and intense tectonic areas, especially the transport infrastructure in Sichuan-Yunnan region, has faced serious safety risks. Therefore, it is important to examine the mechanisms and control the dynamic catastrophe evolution in long tunnels under extreme conditions. The key research areas include: ① multi-field coupling mechanism of tectonic stress fields, strong dynamic fields, and surrounding rock seepage fields, and the evolution and characterization of engineering loads; ② disaster evolution mechanisms of tunnel structures under the coupling of complex tectonic stress and strong seismic-fault dislocation effects; ③ triggering mechanism and control strategy of deep rock bursts under complex geological conditions; ④ risk assessment and resilience enhancement system for long tunnels in extreme environments. The development trend in

the future involves clarifying the disaster-bearing mechanism of engineering sites in extreme environments and project load characteristics, and on this basis, revealing the disaster process and failure mode of engineering structures, developing disaster prevention and mitigation control technology for long tunnel structures in extreme environments, and building a multi-disaster risk assessment and safety regulation and decision-making system for long tunnel structures in extreme environments. A total of 48 core papers relevant to this research front were published between 2018 and 2023. These papers received 1 812 citations, with an average of 37.75 citations per paper.

(8) Advanced oxidation/reduction technology for removing organic pollutants from water

High-risk pollutants, such as pesticides, endocrine disruptors (EDs), and disinfection byproducts in aquatic environments are diverse, harmful, and difficult to remove, posing major challenges to human health and ecosystems. Advanced oxidation/reduction processes (AOPs/ARPs) can produce highly concentrated, highly active intermediate states (such as free radicals, high-valence metals, and hydrated electrons) and achieve detoxification and mineralization of high-risk pollutants through electron transfer or hydrogen extraction and oxygen addition mechanisms. AOPs and AOPs/ARPs have developed into the core units of advanced treatment processes, which have far-reaching strategic significance for ensuring water quality safety and improving human health and welfare. Current research focuses on: ① formation and regulation mechanism of active components in advanced oxidation/reduction systems; ② design and development of efficient, green, and stable new catalysts; ③ investigation and application of selective advanced oxidation/reduction processes under complex water quality; ④ research and optimization of novel advanced oxidation/reduction processes for emerging highly toxic organic pollutants; ⑤ development and application of advanced oxidation/reduction processes under the coupling of new energy structures (light, heat, and electricity). The main development trend in the future involves clarifying the degradation behavior of high-risk pollutants in advanced oxidation/reduction processes under extreme water quality conditions and the mechanism of detoxification transformation, developing innovative technologies for advanced oxidation/reduction coupled with biochemistry, adsorption, membrane filtration, pervaporation, and other multi-process units for the enhanced removal of stable organic pollutants, desalination, and enhancing removal of volatile organics. Meanwhile, attention has also been placed on the construction of a dynamic prevention and control technology system for new pollutants with unknown risks under the assistance of AI, the realization of intelligent recommendations for applicable advanced oxidation/reduction technology, and intelligent optimization of multi-functional catalysts to promote the systematic establishment and promotion of sustainable water treatment technologies. Overall, future research should aim to promote the systematic establishment and application of sustainable water treatment technologies. A total of 473 core papers relevant to this research front were published between 2018 and 2023. These papers received 43 325 citations, with an average of 91.60 citations per paper.

(9) Intelligent design theory for green and low-carbon engineering structures

The intelligent design of green low-carbon engineering structures integrates the concepts of sustainable development, innovations in green building materials, and cutting-edge intelligent design technologies, creating a new paradigm in design theory. This paradigm focuses on selecting sustainable, eco-friendly materials, creating a sustainability evaluation system that covers multi-dimensional indicators, such as carbon emissions and economic benefits, and leveraging AI, especially generative AI, to explore innovative, efficient, and rapid structural designs. The aim is to achieve energy conservation, emission reduction, and cost savings. In response to the national “dual carbon” goals and call for promoting green building materials and low-carbon construction technologies, such as prefabricated steel and timber structures in the “Implementation Plan for Carbon Peaking in Urban and Rural Construction”, as well as seizing the opportunity of the “new infrastructure” initiative to drive the intelligent transformation of civil engineering, it is of great significance to deeply explore the collaborative innovation between green materials and AI technologies in structural design. The main research areas include: ① structural layout design of prefabricated (steel/ timber) structures based on generative AI; ② structural form optimization design using generative AI, graph neural networks, and topology algorithms; ③ detailed structural design guided by physical rules or dual-driven by physics and data; ④ component optimization design based on multi-agent reinforcement learning; ⑤ comprehensive structural design considering carbon emission control and multi-objective resilience; ⑥ sustainable structural design and evaluation considering the multi-dimensional factors, including carbon emissions, economy, and society, throughout the entire life cycle. Future development trends will focus on clarifying

the generative mechanisms of AI in green low-carbon structures, enhancing the physical explainability of AI algorithms, and establishing a scientific quantitative design evaluation system. By integrating reinforcement learning and optimization algorithms, the refinement of local structural design can be further enhanced, thereby minimizing carbon footprint. Ultimately, this will lead to the construction of an autonomous intelligent design system for green, low-carbon engineering structures, thereby providing technical support and theoretical guidance for the green and intelligent transformation of the construction industry. Between 2018 and 2023, 200 core papers related to this research topic were published. These papers received 7 300 citations, with an average of 36.50 citations per paper.

(10) Mechanisms and optimization of built environment health impacts in urban communities

The health impacts of built environments in urban communities refer to the short-term and cumulative health effects that various spatial elements at the community level exert on individuals throughout their lives. Both the United Nations and World Health Organization emphasize the role of urban planning in disease prevention. The “Healthy China” national strategy identifies healthy cities as a key initiative. The promotion of physical and mental health through urban planning is a cutting-edge scientific issue in the international academic community. Given that urban communities serve as the primary spatial context for residents’ daily activities, investigating the mechanisms and optimizing the health impacts of the built environment in these areas is crucial. It can contribute to the development of innovative approaches that enhance population well-being through upstream planning and design processes, as well as downstream environmental interventions. The primary research focuses on: ① theoretical models for spatial health interventions in urban communities, identifying easily modifiable indicators with significant impacts and their thresholds; ② key technologies for the precise diagnosis of health performance of urban community spaces, establishing an evaluation indicator system, and developing assessment tools; ③ efficient optimization methods to enhance the health performance of urban community spaces, and predicting and simulating the effects of interventions to support the selection of planning schemes. Future trends should emphasize the clarification of the full-path mediation mechanisms. Therefore, there is a need to develop cross-scale health diagnosis and evaluation technologies that span the macro to micro levels, along with multi-scene and multi-factor synergistic optimization methods. This will enable a full understanding of the upstream health intervention effects of urban planning and provide scientific evidence for evidence-based practices in promoting healthy urban community planning. A total of 195 core papers relevant to this research front were published between 2018 and 2023. These papers received 9 517 citations, with an average of 48.81 citations per paper.

6.1.2 Interpretations for three key engineering research fronts

6.1.2.1 Mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment

Under the combined influence of climate change and human activities, flood and drought disasters in river basins have shown new trends of increased intensity and frequency. Global warming and large-scale rain belt migration have affected human societal development. Increasingly frequent extreme events that result in flood and drought disasters in river basins carry high levels of uncertainty and unpredictability, posing significant challenges to global water, food, and ecological security. Meanwhile, the accelerated pace of socioeconomic development has further exacerbated the risk of flood and drought disasters. Examining the mechanisms of extreme flood and drought disasters and risk regulation in river basins in changing environments is of great importance for ensuring the stable development of human society. The main research directions are as follows:

1) Multi-source monitoring of flood and drought disasters and data assimilation based on the integration of space, sky, and ground single-observation technologies and models have significant uncertainties in the monitoring, simulation, and prediction of flood and drought disasters. By integrating multi-source data from space, sky, and ground, it is possible to build a three-dimensional observation system for hydrometeorological elements and obtain multi-scale hydrometeorological fusion data. Developing data assimilation methods suited to multi-modal hydrometeorological data will enable high-precision simulations and predictions of flood and drought disasters through the assimilation of hydrological or land surface models.

2) Identification and evolution mechanisms of extreme flood and drought events in river basins in changing environments. In response to the new circumstances of changing rainfall characteristics and land surface factors, intelligent recognition algorithms based on coupled mechanistic and machine learning models will be developed to identify extreme flood and drought events in river basins. These algorithms provide quantitative, refined, and multi-dimensional insights into the mechanisms of occurrence, developmental processes, and distribution characteristics of these events.

3) Threshold and tipping (explosion) point predictions for extreme flood and drought disasters in river basins. By integrating the complex feedback mechanisms of hydrometeorological and ecological processes and human development, this research will focus on the disaster-triggering mechanisms of flood and drought events in river basins and identify their disaster-causing thresholds. Furthermore, it will estimate the trends and potential abrupt changes in flood and drought disasters at different spatial and temporal scales under changing environments, predicting future frequencies, intensities, and tipping (explosion) points.

4) Risk assessment and regulation technologies for sudden disasters, such as flash floods, abrupt droughts, and rapid drought-to-flood transitions. To address the challenges of defining, characterizing, and quantifying sudden flood and drought disasters, research will focus on revealing their clustering mechanisms and disaster-causing effects and developing high-frequency dynamic risk identification and assessment technologies. These studies will examine planning and emergency regulation methods for short-duration extreme flood and drought disasters, focusing on disaster-prone areas and processes.

5) Risk assessment and regulation systems for flood disasters in large and medium-sized cities. Focusing on highly urbanized areas, in this study, risk assessments of rainstorm-induced flood disasters, triggered by typhoons, strong convective weather, and other extreme events, were conducted. This includes the development of multiple platforms, multi-model ensemble forecasting, and early warning methods. A collaborative defense strategy for urban floods based on “retention, storage, diversion, and drainage” will be proposed, establishing a comprehensive flood regulation system from early warning to post-disaster recovery.

Based on the above statistical data, in the research frontier of “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”, Chinese scholars have a certain advantage when compared to their international counterparts and are gradually advancing to a leading position.

As shown in Table 6.1, a total of 151 core papers regarding “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment” were published, with each paper being cited 47.92 times on average. The top five countries in terms of core papers were China, the USA, the UK, Australia, and Germany (Table 6.3). China is one of the most active countries, accounting for 52.32% of core papers. The five countries with the highest citations per paper were Brazil, Australia, the UK, the USA, and Pakistan. Papers published by Chinese authors were cited 45.75 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 6.1, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were Chinese Academy of Sciences, Wuhan University, Tsinghua University, Hohai University, and Nanjing University (Table 6.4). The Chinese Academy of Sciences mainly studies changes in glaciers and their hydrological impacts in the Himalaya and Karakoram regions; groundwater, precipitation, floods, and drought assessment and prediction in the river basins of China and Pakistan; the impact of climate change on water resources and agricultural water resource management; and the role of reservoirs in regulating flood and drought risks. Wuhan University has mainly examined the impacts of climate change on the hydrological cycle, water resources, drought and flood disasters, and hydropower generation in the Yangtze River Basin, as well as how to use remote sensing data and hydrological models to assess and predict these impacts. Tsinghua University mainly examines real-time reservoir operation using recurrent neural networks and distributed hydrological models; the impact of climate change on the yield and water footprint of major crops in Thailand; the spatiotemporal characteristics and causes of wet and dry conditions in the Weihe River Basin, a typical monsoon transition zone in East Asia; and changes in future river annual runoff and hydroclimatic extremes. As illustrated in Figure 6.2, the ten most productive institutions have conducted collaborative studies in this regard.

As listed in Table 6.5, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Brazil. The top

five institutions in terms of citing papers were Chinese Academy of Sciences, Wuhan University, Hohai University, Beijing Normal University, and Nanjing University of Information Science and Technology (Table 6.6).

Based on the statistical data above, research on “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment” is still in its infancy. Compared with their foreign counterparts, Chinese scholars are in a leading position.

In the next decade, the key development directions of this frontier will be to clarify the nonlinear driving response mechanisms between changing environments and flood and drought disasters in river basins, develop forecasting and prediction technologies based on the coupling of AI and mechanistic models, and enhance risk identification and systematic regulation of extreme flood and drought disasters in river basins. Simultaneously, this frontier will trend towards multi-dimensional, refined, systematic, and intelligent development. As extreme flood and drought disasters in river basins become more frequent in changing environments, human society’s exposure and vulnerability to such risks will also increase. The research outcomes from this frontier can be widely applied to ensure water security and public safety, demonstrating great potential for growth (Figure 6.3).

Table 6.3 Countries with the greatest output of core papers on “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	79	52.32	3 614	45.75	2021.1
2	USA	28	18.54	1 785	63.75	2020.4
3	UK	16	10.60	1 030	64.38	2020.5
4	Australia	11	7.28	743	67.55	2020.0
5	Germany	11	7.28	512	46.55	2021.4
6	India	11	7.28	361	32.82	2020.7
7	Brazil	8	5.30	579	72.38	2020.1
8	Pakistan	8	5.30	456	57.00	2020.9
9	Netherlands	8	5.30	426	53.25	2020.5
10	Republic of Korea	8	5.30	302	37.75	2021.6

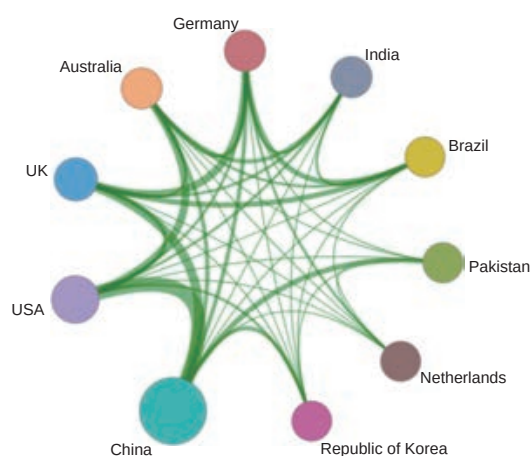


Figure 6.1 Collaboration network among major countries in the engineering research front of “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

Table 6.4 Institutions with the greatest output of core papers on “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	23	15.23	1 051	45.70	2021.1
2	Wuhan University	11	7.28	419	38.09	2020.5
3	Tsinghua University	8	5.30	368	46.00	2021.8
4	Hohai University	8	5.30	241	30.12	2021.4
5	Nanjing University	6	3.97	352	58.67	2020.5
6	Beijing Normal University	6	3.97	242	40.33	2020.8
7	Xi'an University of Technology	4	2.65	356	89.00	2020.0
8	China Meteorological Administration	4	2.65	169	42.25	2021.2
9	China Institute of Water Resources and Hydropower Research	4	2.65	155	38.75	2021.5
10	ETH Zurich	4	2.65	150	37.50	2021.2

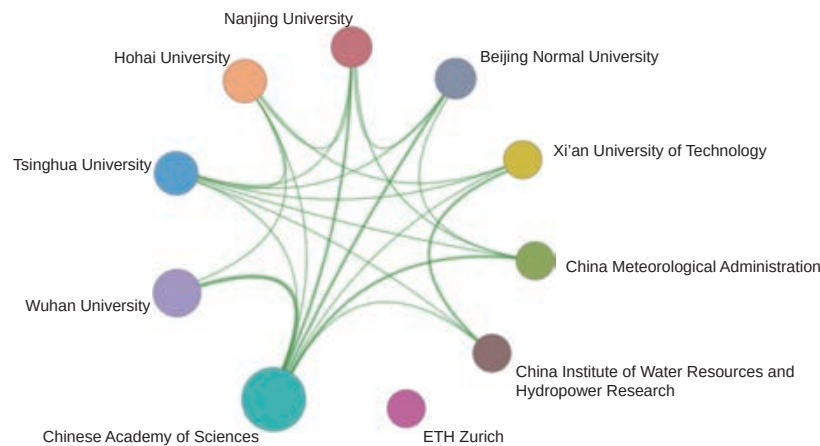


Figure 6.2 Collaboration network among major institutions in the engineering research front of “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

Table 6.5 Countries with the greatest output of citing papers on “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 919	40.35	2022.1
2	USA	1 101	15.22	2022.0
3	India	672	9.29	2022.3
4	UK	393	5.43	2021.8
5	Brazil	372	5.14	2021.9
6	Australia	367	5.07	2021.9
7	Germany	354	4.89	2022.1
8	Iran	337	4.66	2022.0
9	Pakistan	257	3.55	2022.3
10	Canada	243	3.36	2022.0

Table 6.6 Institutions with the greatest output of citing papers on “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	741	34.35	2022.1
2	Wuhan University	242	11.22	2022.1
3	Hohai University	236	10.94	2022.1
4	Beijing Normal University	187	8.67	2022.1
5	Nanjing University of Information Science and Technology	150	6.95	2022.2
6	China Institute of Water Resources and Hydropower Research	133	6.17	2021.7
7	China University of Geosciences	109	5.05	2022.3
8	Tsinghua University	105	4.87	2022.2
9	Sun Yat-sen University	90	4.17	2022.2
10	Xi'an University of Technology	84	3.89	2021.2

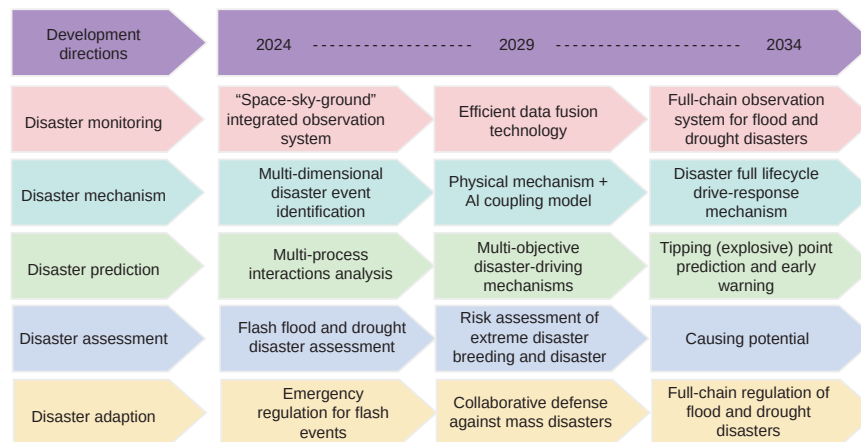


Figure 6.3 Roadmap of the engineering research front of “mechanisms of extreme flood and drought disasters and risk regulation in river basins under changing environment”

6.1.2.2 Urban planning and architectural design methods empowered by large models

The core of the large model-enabled urban planning and architectural design method lies in: ① realizing the digital construction of planning and architectural design methods through multi-modal knowledge enhancement, forming a disciplinary holographic knowledge map, and realizing the analysis and identification of complex theoretical mechanisms; ② provide full-process support for the three key design steps of research, generation, and evaluation through large models. Through the exploration of the aforementioned two dimensions, we can train the design model of “analytic, computable, inferential, and evolvable”, change the design paradigm dominated by personal subjective experience, and realize the intelligentization of the entire process of planning and architectural design. Frontier research directions are mainly reflected in the following aspects.

1) Construction of holographic knowledge map of disciplines: The traditional discipline of cognitive systems, based on personal experience and text knowledge map construction, is fragmented and one-sided, and the theoretical mechanism construction of planning and architecture is still lacking. Simultaneously, as an important part of the theoretical knowledge of urban planning and architectural design, it is difficult to analyze and identify complex multi-modal information and

theoretical mechanisms using traditional methods. This research uses the multi-modal data fusion technology of graphs and texts in a large model to integrate data from different sources and formats, construct a subject holographic knowledge map with full-aperture knowledge, and form a comprehensive analysis and understanding of the previous “divergent” urban planning and architectural design theories. This can effectively promote the digital description and knowledge fusion of the current fragmented multi-modal knowledge of the subject.

2) Intelligent present status judgment: The traditional study of the status quo of cities and buildings has the problems of “unclear characteristics” and “difficult to judge”. Based on knowledge traction and data-driven large-scale model training, it can not only efficiently integrate various material physical elements, such as spatial form, functional composition, architectural texture, and non-material economic and social effects, but also realize the analysis of the status quo feature recognition, refine the evaluation dimensions that meet the needs of the site, establish an evaluation and judgment system that spans large- (urban planning), medium- (urban design), and small-scale (architectural design), and quantitatively evaluate the multi-scale status quo elements, including urban morphological characteristics, block vitality, and architectural style. With the support of massive data, intelligent research, judgment of experts, and multiple dimensions can be realized. Finally, it promotes the transformation of the status quo from a discussion of qualitative experiences to quantitative intelligent judgments.

3) Generative planning and design: The problem of a large model generating image architectural design and urban planning schemes often lies in its insufficient grasp of the spatial scale. To address this problem, based on the image generated by a large model, in this study, a strategy recommendation model is developed according to different scales, clusters, and functions, and explores its generative design method. Based on the external chain of knowledge graphs and research results on intelligent status, generative design is promoted for application in demonstration projects. However, owing to its high text-generation efficiency, a large model can efficiently generate professional text after fine-tuning and manual instructions, thus opening the full link between text generation and image generation to serve generative planning and design.

4) Efficiency evaluation of digital intelligent design: Based on the professional backgrounds of architectural disciplines, the big model can be used to construct multi-scale efficiency measurement models and accurate diagnostic methods for cities, blocks, and buildings in view of the difficulties in planning and design. Under the guidance of a multi-modal knowledge graph, knowledge embedding is performed, and pre-training large-scale model tuning is realized with the support of proprietary datasets. Through the dual-drive training of knowledge and data, the specialized design efficiency of large-scale models is examined and judged. This solves the problem of long time consumption and low reliability of traditional scheme evaluation and realizes the rapid processing of complex information. Simultaneously, the evaluation paradigm dominated by experience is changed to improve the scientificity of the scheme’s evaluation results.

As shown in Table 6.1, a total of 169 core papers on “urban planning and architectural design methods empowered by large models” were published, with each paper being cited 51.30 times on average. The top five countries in terms of core papers were China, the USA, the UK, Australia, and the Republic of Korea (Table 6.7). China is one of the most active countries, accounting for 34.91% of core papers. The five countries with the highest citations per paper were Canada, Singapore, Australia, the UK, and France. Papers published by Chinese authors were cited 47.85 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 6.4, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were the National University of Singapore, Wuhan University, Harbin Institute of Technology, the University of Hong Kong, and Chinese Academy of Sciences (Table 6.8). The National University of Singapore primarily examines the use of machine learning and AI technology to analyze urban spatial data to optimize urban planning, environmental monitoring, and architectural design. Wuhan University is also focusing on new technologies and methods for urban land change simulation, PM2.5, architectural heritage recognition, shear wall structure design, assessment of nonstationary extreme precipitation, medical image segmentation, urban vitality analysis, rice phenology detection, and driver fatigue detection. Harbin Institute of Technology primarily researches the use of AI and machine learning technology to improve data analysis, design optimization, environmental assessment, and health

monitoring in the fields of urban and civil engineering. As illustrated in Figure 6.5, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 6.9, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Germany. The top five institutions in terms of citing papers were Chinese Academy of Sciences, Tsinghua University, Tongji University, Wuhan University, and National University of Singapore (Table 6.10).

Summarizing the above statistics, Chinese scholars have performed well and have become leaders in research on “urban planning and architectural design methods empowered by large models”.

The key development directions of urban planning and architectural design methods enabled by large models over the next ten years are as follows (Figure 6.6):

Table 6.7 Countries with the greatest output of core papers on “urban planning and architectural design methods empowered by large models”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	59	34.91	2 823	47.85	2021.7
2	USA	42	24.85	2 124	50.57	2021.3
3	UK	14	8.28	858	61.29	2021.3
4	Australia	13	7.69	802	61.69	2021.5
5	Republic of Korea	10	5.92	317	31.70	2022.2
6	Singapore	9	5.33	691	76.78	2021.2
7	Germany	9	5.33	319	35.44	2021.6
8	France	8	4.73	428	53.50	2020.0
9	India	7	4.14	313	44.71	2022.0
10	Canada	6	3.55	646	107.67	2021.0

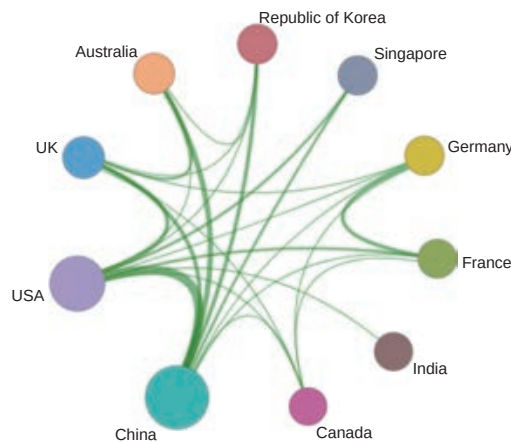


Figure 6.4 Collaboration network among major countries in the engineering research front of “urban planning and architectural design methods empowered by large models”

Table 6.8 Institutions with the greatest output of core papers on “urban planning and architectural design methods empowered by large models”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	National University of Singapore	7	4.14	509	72.71	2021.6
2	Wuhan University	5	2.96	265	53.00	2021.2
3	Harbin Institute of Technology	5	2.96	175	35.00	2021.4
4	The University of Hong Kong	5	2.96	111	22.20	2022.0
5	Chinese Academy of Sciences	4	2.37	239	59.75	2021.2
6	Guangzhou University	4	2.37	176	44.00	2020.2
7	Massachusetts Institute of Technology	4	2.37	126	31.50	2021.0
8	Tsinghua University	4	2.37	104	26.00	2022.5
9	University of Oxford	3	1.78	514	171.33	2020.3
10	ETH Zurich	3	1.78	498	166.00	2021.3

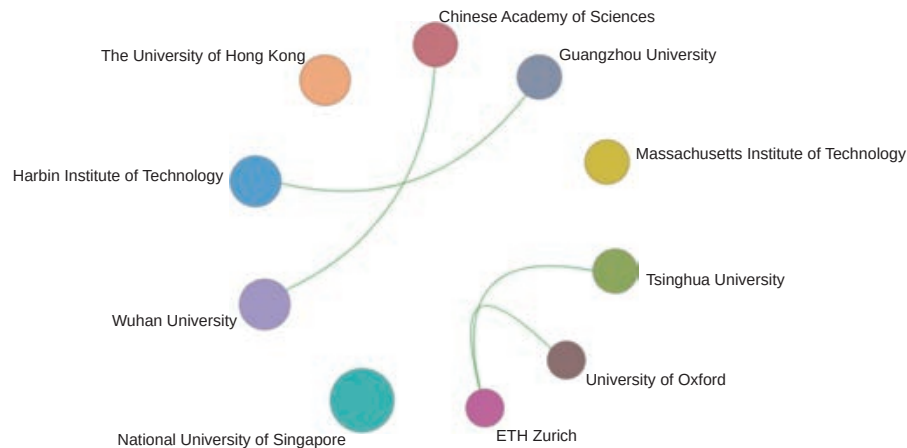


Figure 6.5 Collaboration network among major institutions in the engineering research front of “urban planning and architectural design methods empowered by large models”

Table 6.9 Countries with the greatest output of citing papers on “urban planning and architectural design methods empowered by large models”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	3 322	39.84	2022.4
2	USA	1 424	17.08	2017.2
3	India	644	7.72	2022.4
4	UK	613	7.35	2010.4
5	Germany	425	5.10	2022.2
6	Australia	373	4.47	2022.3
7	Canada	329	3.95	2022.2
8	Italy	327	3.92	2022.3
9	Republic of Korea	324	3.89	2022.4
10	Saudi Arabia	312	3.74	2022.4

Table 6.10 Institutions with the greatest output of citing papers on “urban planning and architectural design methods empowered by large models”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	250	19.81	2022.4
2	Tsinghua University	169	13.39	2022.4
3	Tongji University	128	10.14	2022.4
4	Wuhan University	125	9.90	2022.3
5	National University of Singapore	115	9.11	2022.3
6	Southeast University	86	6.81	2022.4
7	Zhejiang University	82	6.50	2022.6
8	Massachusetts Institute of Technology	77	6.10	2022.4
9	Stanford University	77	6.10	2022.2
10	The Hong Kong Polytechnic University	77	6.10	2022.7

1) Construction of a discipline holographic knowledge map: A large amount of interdisciplinary knowledge in the fields of architectural design and urban planning should be integrated, and the emergence of large models makes the construction of knowledge maps more efficient and qualitative. Collect multi-modal resources, such as discipline-related policies, papers, books, data, and videos, use the method of large models to enable multi-modal knowledge graph fusion and perform tuning through expert dialogue to construct an addictive, interdisciplinary, and multi-modal holographic knowledge graph in the field.

2) Intelligent present status judgment: In the current research and judgment stage, with the aid of large models, intelligent data capture is conducted to quickly read the characteristics of the population, space, culture, and other aspects; generate refined multi-dimensional portraits; and realize intelligent research and judgment from a single dimension to multi dimensions. The large model is used to further refine and summarize the phased conclusions and research results and professionally empower intelligent platform development and project demonstration.

3) Generative planning and design: The problem of a large model generating image architectural design and urban planning schemes often lies in its insufficient grasp of the spatial scale. To address this problem, based on the image generated by a large model, this study constructs a strategy recommendation model according to different scales, clusters, and functions and explores its generative design method. Based on the external chain of knowledge graphs and research results on intelligent status, generative design is promoted for application in demonstration projects. However, owing to its high text-generation efficiency, a large model can generate professional text efficiently after fine-tuning and manual instructions, thus opening up the full link between text generation and image generation to serve generative planning and design.

4) Efficiency evaluation of digital intelligent design: Intelligent planning and design scheme evaluation can overcome the problem of the difficult handling of huge amounts of data owing to time and manpower in the past, and expert experience is easily limited by subjective preferences or inherent thinking. Based on a comprehensive perception of multi-modal knowledge graphs, we can make more accurate and appropriate judgments and responses to current urban planning and design schemes, form an evaluation paradigm from single to comprehensive efficiency, and guide the refined and scientific development of urban design.

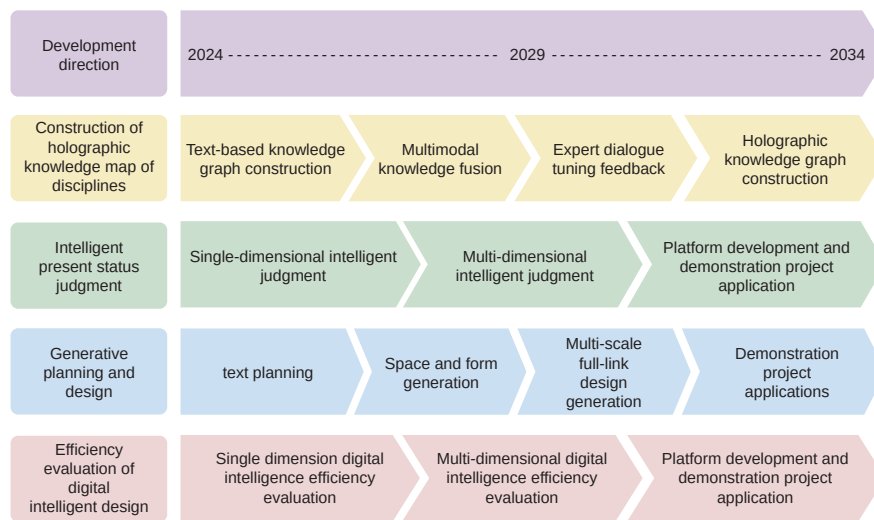


Figure 6.6 Roadmap of the engineering research front of “urban planning and architectural design methods empowered by large models”

6.1.2.3 Intelligent operation and safety assurance of new energy transportation systems

Efficient operating technologies and safety assurance systems for new energy transportation systems are crucial for the integrated development of transportation and energy. Existing research lacks systematic demand modeling and forecasting for multiple energy sources and transportation modes, making it difficult to accurately respond to dynamic changes. Current operational services primarily focus on efficiency optimization, neglecting multi-objective issues, such as energy consumption, efficiency, and carbon emissions across various transportation modes. This leads to low levels of intelligent emergency assurance for infrastructure, resulting in insufficient flexibility and efficiency in responding to complex transportation-energy coupling scenarios. It is essential to explore the multiple attributes of new transportation infrastructure sources, grids, loads, and storage, and develop digital and intelligent methods to transition the new energy transportation system from inefficient to efficient and from high-carbon to low-carbon systems. The main research topics were as follows:

- 1) Forecasting heterogeneous transportation demand and multi-type clean energy supply: Develop a multi-dimensional parameter perception system focused on the characteristics of new energy transportation activities and energy use, and propose a high-precision model structure that integrates transportation activity trajectories, energy consumption behaviors, and spatiotemporal environments to achieve accurate spatiotemporal parameter extraction for transportation activities and energy use. Furthermore, we established a forecasting methodology for short- and long-term energy demands applicable to heterogeneous transportation energy scenarios, predicting the energy demand characteristics of transportation activities in conjunction with different transportation modes, energy types, geographic features, and consumption behaviors. Furthermore, we established forecasting models for clean energy supply from various sources, including solar, wind, and geothermal, responsive to geographic conditions and energy network operations, to comprehensively enhance the supply-demand matching efficiency and flexibility of the new energy transportation system.
- 2) Multi-objective scheduling for green smart mobility systems: Construct a dynamic scheduling and control model for vehicles in multi-modal mobility systems, including new energy buses, shared electric vehicles, and electric ride-hailing services. Given the volatility of new energy outputs, such as grid load, wind, and solar power, as well as the heterogeneity and randomness of travel demand, the objective is to optimize travel efficiency, operational costs, energy consumption, carbon emissions, and fluctuations in grid load. Develop large-scale network human-vehicle-road-pile matching and planning algorithms based on AI to optimize fleet size, vehicle types, speeds, scheduling, routes, charging/discharging combinations, and real-time vehicle dispatching.
- 3) Energy “source-grid-storage” coupling technology responsive to transportation demand: Rationally layout and optimize the

energy infrastructure network of the new energy transportation system and establish a comprehensive management control architecture covering energy collection, distribution, storage, and usage. Construct interactive mechanisms and models for transportation and energy systems considering the spatiotemporal variation characteristics of both environments. Based on this, an efficient dynamic collaboration of the energy source–grid load storage system can be realized through adaptive regulation. This in turn can enhance the energy utilization efficiency of new energy transportation systems under changing conditions and realize real-time coupling configurations between the energy supply and transportation demand.

4) Operation and maintenance of new energy infrastructure and emergency safety assurance technologies: New energy infrastructure (charging facilities, hydrogen refueling stations, storage devices, new energy vehicles, etc.) is characterized by high stock, large increments, high risks, and difficult maintenance. Key technologies for the evolution and early warning of new energy transportation infrastructure conditions and maintaining and enhancing facility performance and addressing rapid responses to failures in transportation operations. This overcomes technical bottlenecks in resource scheduling for repairs and intelligent rescue equipment; forms a repair and rescue technology system for incident prevention, response, and recovery; enhances the safety assurance and resilience recovery capabilities of the new energy transportation system; and achieves integrated operational requirements for autonomous monitoring, analysis, early warning, and response.

As shown in Table 6.1, a total of 335 core papers regarding “intelligent operation and safety assurance of new energy transportation systems” were published, with each paper being cited 65.01 times on average. The top five countries in terms of core papers were China, the USA, the UK, Canada, and India (Table 6.11). China is one of the most active countries, accounting for 44.48% of core papers. The five countries with the highest citations per paper were Germany, the UK, China, Italy, and the USA. Papers published by Chinese authors were cited 74.13 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 6.7, close cooperation is observed among the ten most productive countries.

The five institutions that published the most core papers were Tsinghua University, Chinese Academy of Sciences, Zhejiang University, Harbin Institute of Technology, and Beijing Jiaotong University (Table 6.12). Tsinghua University mainly examines the traffic flow of autonomous vehicles, service pricing, and charging scheduling for electric vehicle-sharing systems and plug-in hybrid electric city buses. Chinese Academy of Sciences mainly studies new developments and applications of intelligent transportation systems, low-temperature lithium-ion battery electrolytes, ammonia energy storage, and triboelectric nanogenerators. Zhejiang University mainly researches technological innovation and environmental benefit analysis in multiple fields, such as intelligent transportation systems, energy efficiency, electric vehicles, environmental monitoring, new materials, and urban carbon cycles. As illustrated in Figure 6.8, the ten most productive institutions have conducted collaborative studies in this regard.

As listed in Table 6.13, the five most active countries in terms of citing papers were China, the USA, India, the UK, and Australia. The top five institutions in terms of citing papers were Chinese Academy of Sciences, Tsinghua University, Zhejiang University, Wuhan University, and Shanghai Jiao Tong University (Table 6.14).

Summarizing the above statistics, Chinese scholars have performed well and have become leaders in the research on “intelligent operation and safety assurance of new energy transportation systems”.

In the next 10 years, key development directions in this frontier will include intelligent demand forecasting and scheduling optimization algorithms for new energy transportation systems, optimization and decision-making systems for energy management, and the development of safety assurance equipment for energy infrastructure. Specifically, in terms of intelligent algorithms, this includes multi-modal transportation demand forecasting, cross-energy-type transportation energy consumption forecasting, and real-time scheduling for large-scale network vehicles and energy. In system development, the goal is adaptive regulation of transportation-energy systems, optimizing energy supply in multiple transportation scenarios, and equipment R&D, focusing on the needs for autonomous monitoring, analysis, early warning, and response of new energy transportation infrastructure, and developing emergency assurance equipment for rapid repair and recovery (Figure 6.9).

Table 6.11 Countries with the greatest output of core papers on “intelligent operation and safety assurance of new energy transportation systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	149	44.48	11 046	74.13	2020.8
2	USA	66	19.70	4 732	71.70	2020.3
3	UK	27	8.06	2 010	74.44	2020.5
4	Canada	19	5.67	1 017	53.53	2020.7
5	India	16	4.78	1 012	63.25	2021.4
6	Germany	15	4.48	1 297	86.47	2020.0
7	Italy	15	4.48	1 104	73.60	2020.3
8	Australia	15	4.48	872	58.13	2020.5
9	France	13	3.88	543	41.77	2019.9
10	Iran	12	3.58	642	53.50	2020.3

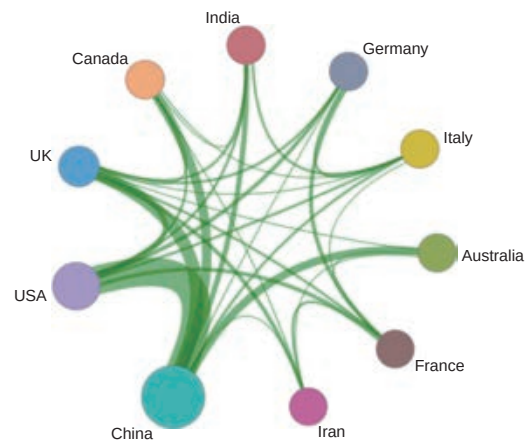


Figure 6.7 Collaboration network among major countries in the engineering research front of “intelligent operation and safety assurance of new energy transportation systems”

Table 6.12 Institutions with the greatest output of core papers on “intelligent operation and safety assurance of new energy transportation systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Tsinghua University	9	2.69	946	105.11	2020.4
2	Chinese Academy of Sciences	9	2.69	789	87.67	2020.9
3	Zhejiang University	7	2.09	356	50.86	2021.1
4	Harbin Institute of Technology	6	1.79	541	90.17	2020.3
5	Beijing Jiaotong University	6	1.79	343	57.17	2021.5
6	Shandong University	6	1.79	244	40.67	2021.5
7	South China University of Technology	5	1.49	380	76.00	2019.2
8	Chongqing University	5	1.49	375	75.00	2021.0
9	Southwest Jiaotong University	5	1.49	339	67.80	2020.2
10	The University of New South Wales	5	1.49	215	43.00	2020.8



Figure 6.8 Collaboration network among major institutions in the engineering research front of “intelligent operation and safety assurance of new energy transportation systems”

Table 6.13 Countries with the greatest output of citing papers on “intelligent operation and safety assurance of new energy transportation systems”

no.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	10 313	48.43	2022.1
2	USA	2 660	12.49	2021.9
3	India	1 531	7.19	2022.2
4	UK	1 347	6.33	2021.9
5	Australia	880	4.13	2021.9
6	Germany	876	4.11	2021.8
7	Republic of Korea	834	3.92	2022.1
8	Canada	774	3.63	2021.9
9	Saudi Arabia	757	3.55	2022.3
10	Italy	697	3.27	2022.0

Table 6.14 Institutions with the greatest output of citing papers on “intelligent operation and safety assurance of new energy transportation systems”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	785	24.61	2022.1
2	Tsinghua University	470	14.73	2022.0
3	Zhejiang University	260	8.15	2022.1
4	Wuhan University	245	7.68	2022.2
5	Shanghai Jiao Tong University	238	7.46	2022.2
6	Chongqing University	210	6.58	2021.9
7	Xi'an Jiaotong University	206	6.46	2021.9
8	Harbin Institute of Technology	199	6.24	2021.7
9	The Hong Kong Polytechnic University	197	6.18	2022.2
10	South China University of Technology	195	6.11	2021.8

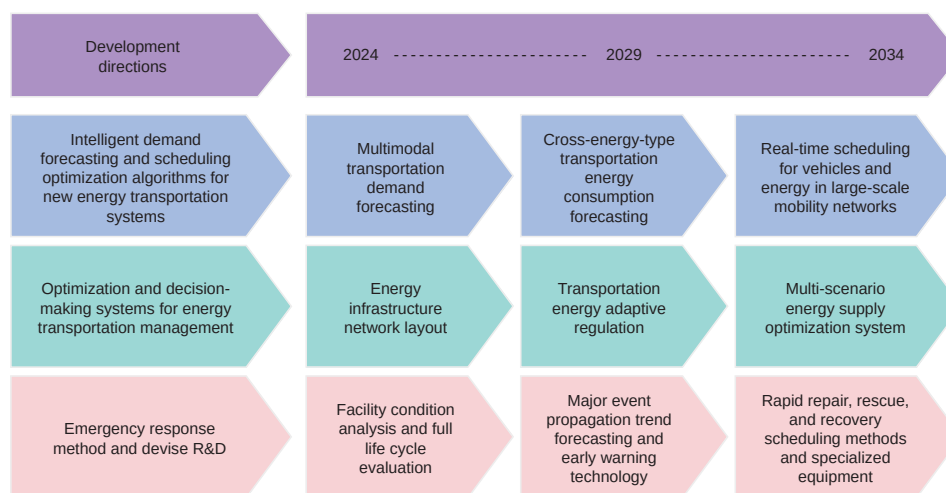


Figure 6.9 Roadmap of the engineering research front of “intelligent operation and safety assurance of new energy transportation systems”

6.2 Engineering development fronts

6.2.1 Trends in the Top 10 engineering development fronts

The Top 10 engineering development fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 6.15. These fronts cover various disciplines, including geotechnical and underground engineering, hydraulic engineering, architectural design and theory, surveying and mapping engineering, construction materials, transportation planning, urban planning and landscaping, municipal engineering, and bridge engineering. The following development fronts were from expert nomination: “intelligent simulation and resilience enhancement technology for urban drainage systems”, “large scale 3D real scene modeling and dynamic updating”, “intelligent coordination and safety assurance of low-altitude and ground transportation systems”, “carbon reduction techniques for planning infrastructure renewal in urban areas”, and “intelligent construction and maintenance of infrastructure under extreme climatic conditions”. The remaining fronts were identified from patent maps and confirmed in expert panel meetings. Table 6.16 presents the annual statistics on patents registered between 2018 and 2023 related to the top ten development fronts.

(1) Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system

Basin-scale hydro-wind-photovoltaic (PV)-storage complementary systems rely on large hydropower bases. It fully utilizes the flexible regulation capabilities of cascade hydropower and energy storage facilities and develops wind and PV power generation projects, achieving integrated resource allocation, coordinated operation, and centralized consumption of renewable energy. Intelligent scheduling technology and equipment for hydro-wind-PV-storage complementarity aim to comprehensively utilize new-generation information technologies such as AI, big data, and the Internet of Things to perform intelligent analysis and decision-making for resource forecasting, complementary scheduling, real-time operation, and market transactions in multi-energy complementary systems. Through intelligent equipment, the scheduling process of clean energy bases is precisely controlled and efficiently managed to improve the comprehensive power generation efficiency, control safety operation risks, and enhance the level of intelligent management of the system. However, in the context of the explosive development of new energy, the hydro-wind-PV-storage complementary system faces a series of new challenges, such as difficulties in balancing power supply and demand, severe curtailment of new energy, and increased risks of safe operation. Traditional scheduling, operation technologies, and equipment can no longer satisfy the new requirements of multi-energy complementary systems. The main technical directions

Table 6.15 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Core papers	Citations	Citations per paper	Mean year
1	Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system	64	1 778	27.78	2021.3
2	Intelligent simulation and resilience enhancement technology for urban drainage systems	229	1 176	5.14	2021.3
3	Large scale 3D real scene modeling and dynamic updating	87	468	5.38	2021.8
4	Intelligent coordination and safety assurance of low-altitude and ground transportation systems	204	4 611	22.60	2021.3
5	Carbon reduction techniques for planning infrastructure renewal in urban areas	108	2 360	21.85	2021.5
6	Structure-function integrated technology of organic composite materials in complex environments	116	319	2.75	2020.8
7	Intelligent construction and maintenance of infrastructure under extreme climatic conditions	134	515	3.84	2021.8
8	Low-cost building-integrated photovoltaic system and implementation technology	48	32	0.67	2021.4
9	Modular building structural system and its intelligent construction	45	119	2.64	2021.2
10	Autonomous unmanned system localization and mapping technology	23	66	2.87	2021.7

Table 6.16 Annual number of core patents published for the Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system	7	4	5	9	23	16
2	Intelligent simulation and resilience enhancement technology for urban drainage systems	15	15	28	49	65	57
3	Large scale 3D real scene modeling and dynamic updating	0	6	8	15	28	30
4	Intelligent coordination and safety assurance of low-altitude and ground transportation systems	17	22	24	31	41	69
5	Carbon reduction techniques for planning infrastructure renewal in urban areas	0	12	18	13	31	34
6	Structure-function integrated technology of organic composite materials in complex environments	15	16	19	22	17	27
7	Intelligent construction and maintenance of infrastructure under extreme climatic conditions	6	7	7	21	44	49
8	Low-cost building-integrated photovoltaic system and implementation technology	4	4	2	10	15	13
9	Modular building structural system and its intelligent construction	2	8	4	9	8	14
10	Autonomous unmanned system localization and mapping technology	0	3	2	2	7	9

include: ① high-precision integrated simulation and forecasting technology for hydro-wind-PV resources; ② multi-scale intelligent scheduling technology for basin hydro-wind-PV-storage complementarity; ③ real-time operation control technology for basin hydro-wind-PV-storage complementarity; ④ indigenous intelligent equipment for the operation and control of basin hydro-wind-PV-storage hybrid system; ⑤ bidding decision-making techniques for basin hydro-wind-PV-storage under the electricity market

environment; ⑥ new operation management modes and technical standards for hydro-wind-PV-storage integration. As the construction scale, number, and scope of multi-energy complementary bases continue to expand, the scheduling and operation of the system will transform from the current experience-driven planned scheduling to data-driven intelligent scheduling, forming a new management model and technical standards for hydro-wind-PV-storage complementary scheduling. This will comprehensively enhance the system's forecasting, decision-making, control, and management capabilities as well as the level of intelligence, promoting the development of integrated renewable energy in river basins. Between 2018 and 2023, 64 patents relevant to this research front were identified. These patents received 1 778 citations with an average of 27.78 citations per patent.

(2) Intelligent simulation and resilience enhancement technology for urban drainage systems

Urban drainage systems are essential for managing stormwater and wastewater, including the collection, conveyance, treatment, and reuse processes. The development of resilient and secure systems is vital for public health and social stability. By harnessing advanced technologies, such as AI, big data, and sophisticated modeling, we can enhance the resilience and intelligence of these systems across their entire lifecycle. These technologies enable the dynamic simulation and optimization of operations, risk management, and environmental impacts. Real-time intervention through control devices improves monitoring, fault diagnosis, process control, and pollution prevention, thereby bolstering the capacity of the system to handle extreme weather and unexpected events. Key development areas include: ① Advanced Monitoring and Warning Systems, implement intelligent systems for real-time monitoring and dynamic alerts at critical nodes; ② Simulation and Control Platforms, develop platforms for optimized simulation, decision support, and smart control to ensure safe operations; ③ Pollution Prevention and Adaptive Strategies, create adaptive scheduling and overflow pollution control measures; ④ Digital Resilience Planning, focus on digital planning, construction, and evaluation of resilient infrastructure. The future of technological development lies in designing adaptable models for extreme climatic conditions and the complexities of urban environments. This includes establishing intelligent networks for monitoring and data transmission, implementing adaptive controls for essential components such as drainage networks and pump stations, and creating integrated management and decision support systems to enhance preventive maintenance and rapid recovery capabilities. Between 2018 and 2023, 229 patents relevant to the research front were registered. These patents received 1 176 citations, with an average of 5.14 citations per patent.

(3) Large scale 3D real scene modeling and dynamic updating

3D real scene is an irreplaceable new type of national infrastructure that reflects and expresses spatiotemporal information on production, life, and ecological space in a realistic, three-dimensional, and temporal manner. In recent years, under the background that the country continues to build a 3D realistic geospatial scene, large-scale 3D real scene modeling and dynamic updating technology have become the forefront of development in this field. Development trends in this research front include: ① large-scale 3D real scene modeling, including geographic scene acquisition and fusion technology, IoT perception data access and fusion technology for real-world 3D, geographic entity semantic modeling technology, etc.; ② 3D real scene database management and dynamic updates, including basic geographic entity and geographic scene adaptation technology, 3D real scene data scale correlation and linkage maintenance technology, quality control technology for basic geographic entity results, etc.; ③ application services, including 3D real scene data interface and service publishing technology, lightweight processing technology for 3D real scene data, security service processing technology for 3D real scene data, etc. Future development trends include automation of large-scale 3D real scene modeling, intelligence updating of 3D real scene dynamics, and smart services of 3D real scenes. Eighty seven patents relevant to this research front were registered between 2018 and 2023. These patents received 468 citations, with an average of 5.38 citations per patent.

(4) Intelligent coordination and safety assurance of low-altitude and ground transportation systems

The low-altitude and ground transportation system refers to an integrated air-ground traffic network within low-altitude airspace and ground road networks, where manned aircraft, unmanned aerial vehicles (UAVs), and ground vehicles operate together. Compared with medium- and high-altitude airspaces, low-altitude airspaces have limited resources, diverse operational scenarios,

high traffic density, strong platform heterogeneity, and complex electromagnetic, magnetic, and wind environments. Their strong coupling with ground transportation systems adds further complexity, making the operation of low-altitude and ground transportation systems highly complex, with severe safety challenges. Research on intelligent coordination of low-altitude and ground transportation systems is of great significance for ensuring traffic safety and promoting the development of low-altitude economies. The main research directions include: ① integrated air-space-ground intelligent sensing of the operational situation and multitarget collaborative monitoring of air-ground transportation system; ② ultra-real-time simulation and risk reduction of digital twins in air-ground transportation system; ③ proactive collision avoidance and coordinated operation among manned aircraft, UAVs, and ground vehicles; ④ intelligent decision-making and risk control in air-ground transportation system management based on digital twin technology. Future development trends focus on achieving precise sensing and risk deduction for multitarget collaborative operations in low-altitude and ground transportation systems, optimizing system safety, and developing prevention strategies through digital twin technology. On this basis, integrating multi-source air-space-ground information will enable dynamic prediction and proactive risk prevention for air-ground transportation system operations, promote intelligent and automated airspace management, accelerate the construction of emergency response systems, and build an intelligent and collaborative safety management system for air-ground transportation. Between 2018 and 2023, 204 patents relevant to the research front were registered. These patents received 4 611 citations, with an average of 22.60 citations per patent.

(5) Carbon reduction techniques for planning infrastructure renewal in urban areas

Infrastructure planning and carbon reduction technology refers to technology that achieves the carbon emission reduction target throughout the entire life cycle of infrastructure, from planning and construction to operation and maintenance, through rational spatial layout, active policy guidance, and fine management. Unlike engineering techniques, planning carbon reduction techniques consider carbon emission reduction from a strategic and global perspective, focusing more on the carbon emissions of the entire life cycle of infrastructure. The implementation methods favor the adjustment of the spatial layout of various types of facilities as well as the formulation of various policies and indicators. Infrastructure, which is the backbone of urban operations, plays a crucial role in maintaining urban functions. In recent years, many energy consumption and carbon emission problems in the system operation and planning and construction of infrastructure exist, and it is of great significance to study the planning and carbon reduction technologies for the renewal of existing infrastructure in the context of “dual-carbon” and sustainable development goals. Currently, the main technical directions of this technology include: ① the entire life cycle carbon footprint assessment of infrastructure; ② the spatial layout and regulation control optimization of distributed integrated energy peaking facilities; ③ the scale, utilization, and spatial layout of renewable energy sources, such as solar energy, wind power generation, and ground-source heat pumps; ④ the optimization of recycling and management systems for solid waste; ⑤ the application and spatial reservation of green infrastructures for water supply and treatment; ⑥ the establishment of a support system for intelligent governance of carbon emissions throughout the entire life cycle of infrastructure. Currently, the research and practice of carbon reduction technologies for infrastructure renewal in existing urban areas mainly focus on three core areas: carbon footprint assessment, optimization of the spatial layout of facilities, and establishment of intelligent governance systems. Future development trends will further clarify the carbon footprint of the entire life cycle of infrastructure, promote the deep integration of facilities and urban spaces, and endeavor to build comprehensive infrastructure that integrates multiple systems. Simultaneously, smart technologies will be strengthened for accurate carbon emission forecasting and spatial and temporal regulation of energy, as well as for the formulation of more effective policies and standards to realize green, low-carbon, and sustainable renewal of urban infrastructure. A total of 108 patents relevant to this research front were registered between 2018 and 2023. These patents received 2 360 citations, with an average of 21.85 citations per patent.

(6) Structure-function integrated technology of organic composite materials in complex environments

The structure-function integrated technology of organic composite materials in complex environments is an advanced approach that combines structural and functional properties. It was designed to satisfy the demands of multi-functionality, durability, and adaptability in civil engineering applications exposed to complex conditions. This technology integrates the mechanical performance of organic composites with functionalities, such as self-healing, corrosion resistance, electrical conductivity,

and thermal insulation. Consequently, it ensures long-term stability and performance in challenging environments, including marine conditions, extreme temperatures, high humidity, and corrosive atmospheres. The key technological directions, include four aspects: ① Self-healing technology, which introduces microcapsules or self-healing mechanisms, allowing the material to autonomously heal cracks and minor damage caused by external forces; ② Interface enhancement and multi-functional surface modification technology, which improves the interfacial bonding strength and surface functionality of organic composites through the incorporation of nanomaterials (such as carbon nanotubes or graphene) and the application of multi-functional surface coatings (e.g., corrosion resistance, wear resistance, and UV protection); ③ Conductive and sensing composite technology, which embeds conductive fibers or conductive polymers to endow the material with sensing and monitoring capabilities; ④ Flame retardant and thermal insulation technology, where the use of flame retardants or phase change materials enables organic composites to maintain effective thermal and fire resistance under high-temperature conditions. The development of structure-function integrated organic composites relies increasingly on the convergence of high-performance materials and advanced fabrication processes. Techniques, such as 3D printing, biomimetic design, nanotechnology, and intelligent manufacturing, further enhance their multi-functionality. This technology is expected to have profound impacts across sectors such as marine engineering, aerospace, and infrastructure construction. A total of 116 patents relevant to this research front were registered between 2018 and 2023. These patents received 319 citations, with an average of 2.75 citations per patent.

(7) Intelligent construction and maintenance of infrastructure under extreme climatic conditions

The intelligent construction and maintenance of infrastructure under extreme climatic conditions (extremely high and low temperatures, heavy precipitation, snowstorms, and typhoons) refers to the use of advanced information technologies, theories, and equipment, such as integrated sensing, machine learning, intelligent analysis, and complex system modeling, to establish models that analyze, learn, and reason based on multi-source real-time data. This enables a full-scale simulation of disaster response, condition evolution, and resilience recovery of the infrastructure, thereby ensuring its overall safety, reliability, functionality, and resilience under extreme climatic conditions. The research directions include: ① real-time sensing and integrated identification technologies for multi-dimensional and multi-modal infrastructure states based on complex multi-sensor networks; ② foundational theories for intelligent construction of infrastructure in extreme climatic environments; ③ data, knowledge, and physics-coupled digital twin modeling methods for complex infrastructure systems; ④ mechanisms of chain disasters and spatiotemporal evolution patterns of infrastructure under typical extreme climatic conditions; ⑤ online sensing and event-driven real-time evaluation, intelligent optimization, and online decision-making methods for infrastructure maintenance strategies. Future development trends focus on elucidating the disaster development mechanisms of large-scale distributed infrastructure under extreme climatic conditions; identifying and predicting risks through integrated and distributed sensing methods; and exploring new models of design, construction, and operation and maintenance that are resilient, recoverable, controllable in disaster impact, and sustainable. Between 2018 and 2023, 134 patents relevant to this research front were identified. These patents received 515 citations, with an average of 3.84 citations per patent.

(8) Low-cost building-integrated photovoltaic system and implementation technology

Low-cost building-integrated photovoltaic (BIPV) systems and implementation technologies involve close integration of photovoltaic power generation systems with the design and construction of buildings. Embedding solar cells into building envelope structures, such as roofs, walls, and windows, achieves a high level of integration between functionality and aesthetics while also reducing system costs. Compared with traditional photovoltaic systems, BIPV not only provides energy but also serves as building materials that offer insulation, soundproofing, and waterproofing. BIPV enables building envelopes to meet basic functional requirements while generating electricity, thereby achieving energy self-sufficiency and contributing to carbon neutrality in the building sector. The main technological directions include: ① developing new, high-efficiency, low-cost photovoltaic materials; ② lightweight and flexible photovoltaic modules adaptable to curved or irregular building facades and roofs; ③ integrated BIPV module design and modular efficient construction techniques; ④ BIPV/T combined technologies for various applications; ⑤ energy management systems for flexible energy use in building complexes. The focus of BIPV technology involves further improvement of energy conversion and utilization efficiency, significantly reducing production and construction

costs, and promoting widespread application and rapid adoption of this technology while ensuring efficient energy production and intelligent distribution. Forty-eight patents relevant to this research front were registered between 2018 and 2023. These patents received 32 citations with an average of 0.67 citations per patent.

(9) Modular building structural system and its intelligent construction

A modular building structural system and its intelligent construction technology refer to the process of dividing a building into several modular units and efficiently completing construction processes of structure, decoration, water and electricity, equipment pipelines, bathroom facilities, etc., of a module on an intelligent production line of a modern factory. Intelligent equipment is used on-site to quickly and reliably assemble various modules into an entire building. This technology moves the building construction process from the site to the intelligent factory, which significantly shortens the construction period, reduces construction difficulty, and achieves the goal of “building a house, such as a car”. It is currently the most industrialized green and intelligent construction method in the construction industry. Intelligent modular buildings have achieved standardized design, intelligent production, green construction, integrated decoration, and digital management in construction, fundamentally overcoming the shortcomings of traditional construction methods, effectively eliminating common problems in traditional buildings, and connecting the entire construction process of design, processing, decoration, and construction. They have realized highly specialized collaboration upstream and downstream in the construction industry chain, promoting the transformation and upgrading of the construction industry toward refinement, low carbonization, and intelligence in all aspects of construction. The main technical directions of modular building structural systems and their intelligent construction include: ① high-performance structural systems and resilient disaster prevention for modular buildings; ② collaborative design and construction technologies for the entire process of modular buildings; ③ efficient connection technologies for modular buildings; ④ intelligent manufacturing and construction technologies for modular buildings. The technical focus is on fully utilizing information technologies, such as big data, AI, BIM, and construction robots, to develop new connecting technologies, structural systems, equipment, and algorithms involved in key processes, such as design, processing, decoration, and construction, to achieve resilient, low-carbon, and intelligent construction of modular building structures. Forty-five patents relevant to this research front were registered between 2018 and 2023. These patents received 119 citations, with an average of 2.64 citations per patent.

(10) Autonomous unmanned system localization and mapping technology

Accurately constructing maps and locating in dynamic unknown environments is a major challenge faced by autonomous unmanned systems such as drones, unmanned vehicles, and unmanned boats. Autonomous unmanned system location and map construction technology iteratively construct a map that expresses the spatial characteristics of the surrounding environment using onboard sensors and estimates the position information of the unmanned system relative to nearby points of interest/obstacles within the map. The development trends in this research front include: ① visual simultaneous localization and mapping (SLAM), the sensor types mainly including monocular, binocular, and RGB-D cameras; ② LiDAR SLAM, which is more robust to lighting conditions than visual SLAM; ③ Multi sensor fusion SLAM, typical sensor fusion techniques including particle filters, Kalman filters, and factor graphs optimized via nonlinear least-squares optimizers. Future development trends include: ① Semantic SLAM, which extracts environmental semantic information based on deep learning methods to enhance the perception and understanding ability of SLAM technology in complex scenes; ② Multi robot SLAM. Twenty-three patents relevant to this research front were registered between 2018 and 2023. These patents received 66 citations, with an average of 2.87 citations per patent.

6.2.2 Interpretations for three key engineering development fronts

6.2.2.1 Intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system

The basin hydro-wind-photovoltaic (PV)-storage complementary system represents both China’s innovative model and wisdom in contributing to the global energy transition as well as a key direction for the future development of China’s hydropower and the low-carbon transformation of its energy system. Currently, major hydropower bases along Yalong, Jinsha, and Lancang rivers have

already proposed integrated planning schemes and have begun pilot construction. Once completed, the total installed capacity is expected to reach two to ten times the currently planned hydropower capacity, forming several 10-million-kilowatt or even 100-million-kilowatt hydro-wind-PV-storage clean energy bases. These bases are 10-million-kilowatt multi-source and multi-grid hybrid power generation systems comprising more than 100 power stations of different types, scales, and transmission modes. Hydropower, wind, PV, and energy-storage power stations are closely coupled through complex hydraulic and topological power structures. They possess the new characteristics of cascade hydraulic circulation connections and multi-energy mutual feedback transformation. Significant changes have occurred in the system structure, mutual feedback relationships, and operational rules. Scientifically determining the scheduling methods of various power sources and efficiently managing and controlling multiple types of units and equipment are unprecedented in China and worldwide. It is critical to promote the integrated development of renewable energy and aid in achieving the “dual carbon” goals.

The cutting-edge research and development directions for intelligent scheduling technology and equipment for basin hydro-wind-PV-storage complementarity currently include the following:

- 1) High-precision integrated simulation and forecasting technology for hydro-wind-PV resources, including “space-air-ground” collaborative intelligent perception technology for hydro-wind-PV resources, high-precision and high-resolution integrated simulation technology for hydro-wind-PV resources suitable for complex terrain conditions in southwest and northwest China, and AI-based multi-scale forecasting and error correction technology for hydro-wind-PV integration.
- 2) Multi-scale intelligent scheduling technology for basin hydro-wind-PV-storage complementarity, including water–energy coupling mechanism and mutual feedback transformation relationship of the multi-energy complementary system, flexibility quantification and enhancement technology for hydropower under high-proportion new energy conditions, multi-scale intelligent scheduling technology for multi-energy complementarity oriented to power and energy balance, scheduling risk conduction mechanism and optimization control technology of the multi-energy complementary system, and efficient high-dimensional nonlinear optimization technology for hydro-wind-PV-storage complementarity scheduling.
- 3) Real-time operation control technology for basin hydro-wind-PV-storage complementarity, including stability analysis technology for basin hydro-wind-PV-storage complementary operation, core algorithms for automatic generation control of basin hydro-wind-PV complementarity, and intelligent control technology for the frequency and voltage of hydro-wind-PV-storage multi-type power sources under a high proportion of new energy and power electronic equipment.
- 4) Indigenous intelligent equipment for operation and control of basin hydro-wind-PV-storage hybrid system, including a fully indigenous intelligent control and management platform for the integrated operation of the basin hydro-wind-PV-storage system, core equipment, industrial control software for intelligent power generation control of multi-energy complementarity, intelligent decision-making systems for integrated operation management of hydro-wind-PV-storage systems, etc.
- 5) Bidding decision-making techniques for basin hydro-wind-PV-storage in the electricity market environment, including a mechanism design for multi-energy complementary systems to participate in the electricity market, electricity market supply demand forecasting technology based on large AI models, volume-price bidding technology for the joint participation of basin hydro-wind-PV-storage systems in multiple electricity markets, and decision-making technology for basin hydro-wind-PV-storage complementary scheduling considering participation in multiple electricity markets.
- 6) New operational management modes and technical standards for hydro-wind-PV-storage integration, including grid-source-coordinated intelligent operational management modes for basin hydro-wind-PV-storage, business systems for complementary operational management of basin hydro-wind-PV-storage complementarity, and technical standards for integrated operational management of basin hydro-wind-PV-storage complementarity.

As listed in Table 6.15, 64 patents related to this topic were registered, with each patent cited 27.78 times on average. The countries that registered the most patents were China, the USA, and Argentina (Table 6.17). China was at the forefront of development, contributing 71.88% of its patents. The number of citations per patent for Chinese patents was 4.70.

The three institutions that produced the most patents were Resilience Financing, Inc., Enrique Menotti Pescarmona, and Hohai University (Table 6.18). Resilience financing, Inc. in the USA mainly studies the use of AI and data analysis to improve engineering management. Hohai University mainly researches the capacity configuration of water-wind-light-storage complementary pump stations, multi-energy complementary scheduling methods, the optimal capacity configuration of multi-energy complementary systems.

The future development of this frontier in the coming ten years will involve multi-energy complementary system resource forecasting, scheduling methods, real-time operation, control equipment, power trading, management models, and technical standards. As the capacity and coverage of multi-energy complementary bases in river basins continue to expand, the contradiction between new energy consumption and the safe and stable operation of power systems is becoming increasingly prominent. This research can effectively overcome difficulties such as power and energy imbalances in multi-energy complementary systems, serious wind and solar power curtailment, and unit regulation delays. It can achieve coordinated scheduling, operational decision-making, and intelligent management of over hundred different types of power stations and thousands of different units, demonstrating enormous development potential (Figure 6.10).

Table 6.17 Countries with the greatest output of core patents on “intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	46	71.88	216	12.15	4.70
2	USA	11	17.19	822	46.23	74.73
3	Argentina	5	7.81	740	41.62	148.00
4	Indonesia	1	1.56	0	0.00	0.00
5	Republic of Korea	1	1.56	0	0.00	0.00

Table 6.18 Institutions with the greatest output of core patents on the “intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Resilience Financing, Inc.	9	14.06	452	25.42	50.22
2	Enrique Menotti Pescarmona	6	9.38	1 110	62.43	185.00
3	Hohai University	4	6.25	36	2.02	9.00
4	China Three Gorges Corporation	3	4.69	3	0.17	1.00
5	State Grid Corporation of China	2	3.12	27	1.52	13.50
6	Institute of Agricultural Resources and Regional Planning, CAAS	2	3.12	25	1.41	12.50
7	Wuhan University	2	3.12	18	1.01	9.00
8	Shenyang University	2	3.12	9	0.51	4.50
9	Sichuan University	2	3.12	4	0.22	2.00
10	Institute of Geographic Sciences and Natural Resources Research, CAS	2	3.12	3	0.17	1.50

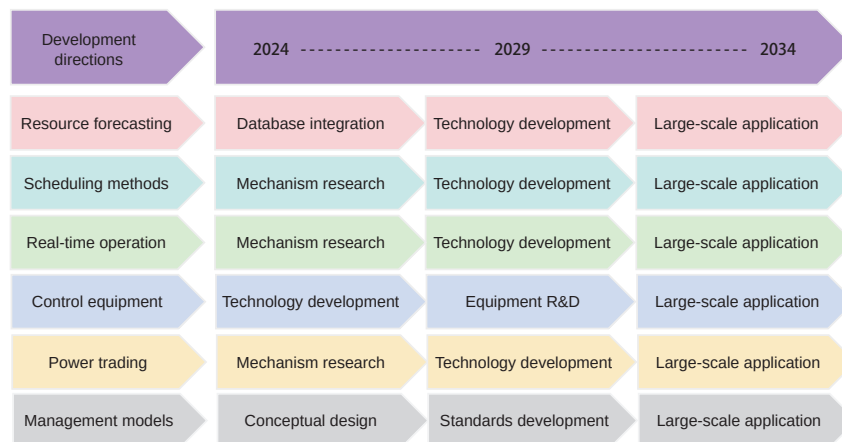


Figure 6.10 Roadmap of the engineering development front of “intelligent scheduling technology and equipment for hydro-wind-photovoltaic-storage hybrid system”

6.2.2.2 Intelligent simulation and resilience enhancement technology for urban drainage systems

Extreme weather events, particularly intense rainfall, pose a critical threat to urban safety and the reliability of drainage systems. Challenges, such as outdated design standards, aging infrastructure, and limited automation, result in high energy consumption, carbon emissions, and low resilience, restricting the ability to manage extreme weather and floods. To address these issues, it is crucial to systematically gather and analyze historical data across various scales to develop climate-adaptive designs and operational models. This includes creating sophisticated monitoring and control methods tailored to the complexity of urban drainage systems, and establishing sustainable management techniques to enhance preventive maintenance and rapid recovery.

New strategies for smart management have emerged owing to advancements in AI, big data, and modeling. Key development areas include: ① Advanced monitoring: Implementation of integrated sensors for water metrics and IoT devices; Optimize the acquisition of unstructured data and the strategic placement of sensors for critical nodes like drainage networks and flood-prone areas. ② Innovative diagnosis and repair: Employ precise technologies for identifying and repairing issues in mixed or damaged drainage networks, utilizing non-invasive detection and repair methods. ③ Adaptive scheduling systems: Develop real-time feedback control mechanisms and optimize system compatibility at various levels, incorporating both local and global strategies for integrated watershed management and comprehensive. ④ Pollution control: Utilization of bioretention, rainwater collection, and advanced storage and treatment systems. Implement predictive control technologies to manage pollution from source to endpoint. ⑤ Resilient Infrastructure Planning. Focus on green infrastructure to manage runoff and pollution, ensure lifecycle water quality, and integrate systems for comprehensive water management. ⑥ Unify simulation and management platforms: Develop precise models for integrated systems by combining advanced simulation software with comprehensive platforms that enhance resilience and operational management.

As listed in Table 6.15, 229 patents related to this front were registered, with each patent cited 5.14 times on average. China, India, and the USA registered the most patents (Table 6.19). China was at the forefront of development, contributing 93.45% of the patents. The number of citations per patent for Chinese patents was 2.03. Cooperation between these countries is rare (Figure 6.11).

The three institutions that produced the most patents were Enrique Menotti Pescarmona, Chongqing City Investment Infrastructure Construction Co., Ltd., and the Power Construction Corporation of China (Table 6.20). In Argentina, Enrique

Menotti Pescarmona mainly studies the hydrological analysis and management processes and systems of river basins, involving networks of meteorological stations, artificial drainage systems, management of natural and artificial reservoirs, and simulation calculations of hydrological maps. Chongqing City Investment Infrastructure Construction Co., Ltd. primarily researches the methods and structures of intelligent anti-drainage systems, including maintainable design, BIM-technology-based pressure monitoring management modules, and configurations of side drainage pipes and annular blind drainage pipes. The Power Construction Corporation of China mainly studies urban intelligent drainage systems, including rainwater and sewage collection, sponge city rainwater discharge, and plant-network-river integrated intelligent scheduling methods, all integrated with sensors and automated control technologies.

The development of this front in the coming ten years involves smart monitoring, smart diagnosis, smart scheduling, facility construction, and integrated management (Figure 6.12).

Table 6.19 Countries with the greatest output of core patents on “intelligent simulation and resilience enhancement technology for urban drainage systems”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	214	93.45	434	36.90	2.03
2	India	9	3.93	2	0.17	0.22
3	USA	4	1.75	370	31.46	92.50
4	Argentina	3	1.31	370	31.46	123.33
5	Ecuador	1	0.44	0	0.00	0.00
6	Spain	1	0.44	0	0.00	0.00
7	Philippines	1	0.44	0	0.00	0.00
8	Saudi Arabia	1	0.44	0	0.00	0.00

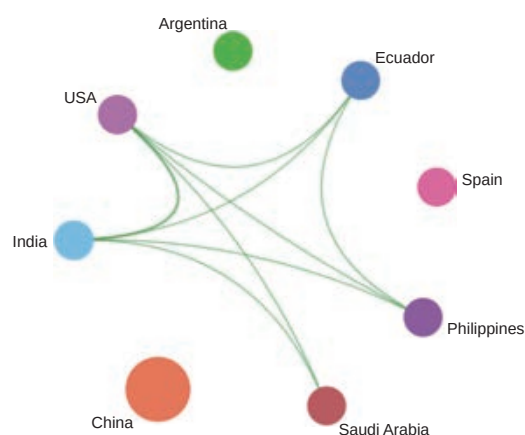


Figure 6.11 Collaboration network among major countries in the engineering development front of “intelligent simulation and resilience enhancement technology for urban drainage systems”

Table 6.20 Institutions with the greatest output of core patents on the “intelligent simulation and resilience enhancement technology for urban drainage systems”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Enrique Menotti Pescarmona	4	1.75	740	62.93	185.00
2	Chongqing City Investment Infrastructure Construction Co., Ltd.	4	1.75	5	0.43	1.25
3	Power Construction Corporation of China	4	1.75	5	0.43	1.25
4	Nanjing Gaoli Construction Machinery Co., Ltd.	3	1.31	27	2.30	9.00
5	Guangzhou Railway Polytechnic (Guangzhou Railway Machinery School)	3	1.31	0	0.00	0.00
6	Hohai University	3	1.31	0	0.00	0.00
7	China State Construction Engineering Corporation	2	0.87	16	1.36	8.00
8	China Metallurgical Group Corporation	2	0.87	10	0.85	5.00
9	Shandong University	2	0.87	10	0.85	5.00
10	Zhejiang University	2	0.87	9	0.77	4.50

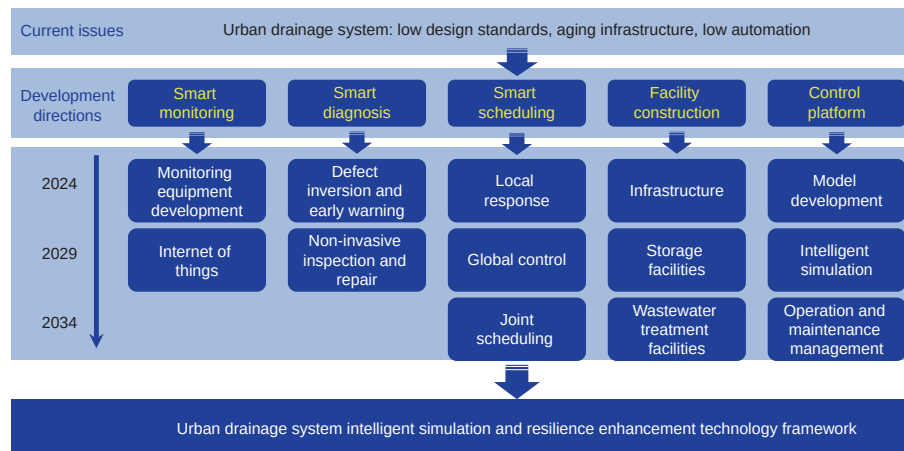


Figure 6.12 Roadmap of the engineering development front of “intelligent simulation and resilience enhancement technology for urban drainage systems”

6.2.2.3 Large scale 3D real scene modeling and dynamic updating

3D real scene is an irreplaceable new type of national infrastructure that reflects and expresses spatiotemporal information on production, life, and ecological space in a realistic, three-dimensional, and temporal manner. The data products can be divided into three levels: terrain-level 3D real scenes, city-level 3D real scenes, and component-level 3D real scenes. In recent years, under the background that the country continues to build a 3D realistic geospatial scene, large-scale 3D real scene modeling and dynamic updating technology have become the forefront of development in this field. The development trends on this research front include the following:

1) Large-scale 3D real scene modeling automation, including geographic scene acquisition and fusion technology, IoT perception data access, fusion technology for real-world 3D, and geographic entity semantic modeling technology. Space satellite photography, aerial photography, ground laser scanning, Internet of Things perception, volunteer mobile phone shooting, and other means of building space-air-ground-human multi-source data acquisition technology are used to achieve large-scale real three-dimensional data acquisition and modeling by multi-source data fusion and intelligent processing.

2) Intelligent management and dynamic updating of the 3D real scene database, including basic geographic entities and geographic scene adaptation technology, stepless mapping techniques for basic geographic entities, spatiotemporal analysis technology for 3D real scenes, data scale correlation and linkage maintenance technology for 3D real scenes, and quality control technology for basic geographic entity results. Integrating diverse data from various geographic scenarios, establishing a distributed database and management system with distributed storage of massive heterogeneous data resources and centralized logic, and achieving the collaborative maintenance of geographic entities, geographic scenes, and other 3D real scene data.

3) Smart services include 3D real scene data interfaces and service publishing technology, lightweight processing technology for 3D real scene data, and security service processing technology for 3D real scene data. Supported by the information infrastructure of cloud network integration and cross-domain interconnection, it provides service capabilities such as spatiotemporal connectivity, spatiotemporal computing, and spatiotemporal intelligence through the construction of dynamic service computing and open technology ecology.

Research institutions that produced the most achievements in this field include Chinese Academy of Surveying & Mapping, National Geomatics Center of China, Wuhan University, Shenzhen University and Southwest Jiaotong University, etc. The three organizations that produced the most patents were Wuhan University, Chinese Academy of Surveying & Mapping and National Geomatics Center of China.

As listed in Table 6.15, 87 patents related to this front were registered, with each patent cited 5.38 times on average. China and the USA registered the most patents (Table 6.21). China was at the forefront of development, contributing 97.70% of the patents. The number of citations per patent for Chinese patents was 4.67.

The three institutions that produced the most patents were Wuhan University, the State Grid Corporation of China, and Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences) (Table 6.22). Wuhan

Table 6.21 Countries with the greatest output of core patents on “large scale 3D real scene modeling and dynamic updating”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	85	97.70	397	84.83	4.67
2	USA	2	2.30	71	15.17	35.50

Table 6.22 Institutions with the greatest output of core patents on the “large scale 3D real scene modeling and dynamic updating”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Wuhan University	5	5.75	13	2.78	2.60
2	State Grid Corporation of China	5	5.75	2	0.43	0.40
3	Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences)	3	3.45	57	12.18	19.00
4	Terra Creating Digital Technology (Beijing) Co., Ltd.	3	3.45	21	4.49	7.00
5	China State Construction Engineering Corporation	3	3.45	18	3.85	6.00
6	China Railway Construction Corporation	2	2.30	22	4.70	11.00
7	China Railway Group Limited	2	2.30	13	2.78	6.50
8	Wuhan Dashi Wisdom Technology Co., Ltd.	2	2.30	11	2.35	5.50
9	Changjiang Spatial Information Technology Engineering (Wuhan) Co., Ltd.	2	2.30	5	1.07	2.50
10	Guangdong South Digital Technology Co., Ltd.	2	2.30	3	0.64	1.50

University mainly studies technologies such as the 3D reconstruction of indoor and urban structures based on 2D videos, air-ground image consistency feature learning, building extraction from live-action 3D models, orthographic image generation, panoramic data, and automatic separation of ground and non-ground models. The State Grid Corporation of China mainly researches 3D realistic modeling and construction quality detection technologies for power systems based on point cloud data fitting, GIS platforms, power infrastructure construction systems, air-ground integrated joint modeling methods, and fatigue life analysis of oil buffers in SF6 circuit breaker operating mechanisms. The Wuhan Center China Geological Survey (Central South China Innovation Center for Geosciences) primarily studies the input of remote-sensing interpretation marks into catastrophe evolution identification models for potential landslide hazard points. Cooperation between these institutions is rare (Figure 6.13).

The future development of this front in the coming ten years involves precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, a combination of spatial geodetic technology, and geocentric motion modeling (Figure 6.14).

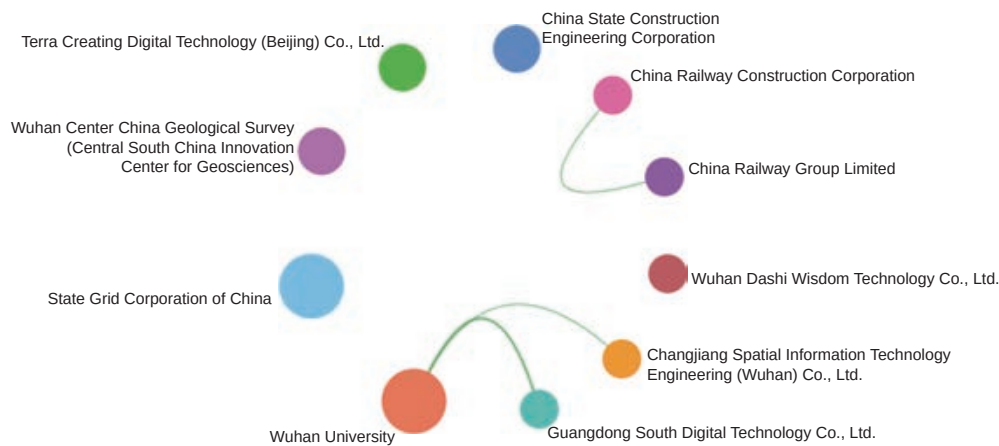


Figure 6.13 Collaboration network among major institutions in the engineering development front of "large scale 3D real scene modeling and dynamic updating"

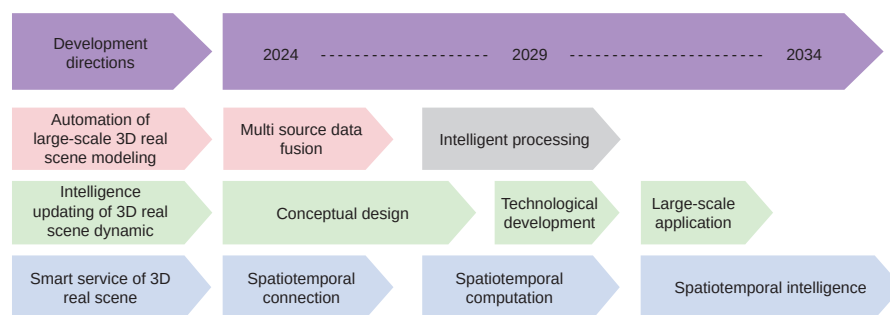


Figure 6.14 Roadmap of the engineering development front of "large scale 3D real scene modeling and dynamic updating"

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Chapter 7 Environmental and Light Textile Engineering Fronts



7.1 Engineering research fronts

7.1.1 Trends in the Top 10 engineering research fronts

The top ten engineering research fronts in the field of environmental and light textile engineering include the subfields of environmental science, meteorological science, marine science, food science, textile science, and light industry science. The citation statistics for these research fronts and the annual number of core papers published for each research front between 2018 and 2023 are summarized in Tables 7.1 and 7.2, respectively.

(1) Synergistic effects of pollution reduction and carbon mitigation in energy transition

Currently, the world contends with two critical challenges: addressing climate change and controlling environmental pollution. Pollution reduction primarily centers on curtailing hazardous substances generated in industrial production and transportation sectors, including particulate matter, sulfur dioxide, nitrogen oxides, aiming to enhance air quality and mitigate adverse impacts on public health. Carbon reduction, conversely, is geared toward reducing emissions of greenhouse gases, such as carbon dioxide. Under the framework of energy transition, a pronounced synergy exists between these two initiatives. An illustrative case is the shift from coal-fired power generation to wind, solar, or hydropower, which significantly curtails greenhouse gas emissions while also reducing particulate pollution associated with coal mining, processing, and combustion. Nonetheless, actualizing the co-benefits of pollution and carbon reduction calls for foundational work in path quantification, scientific planning, and policy formulation.

Enhancing synergies in pollution and carbon reduction within the context of energy transition necessitates further integration

Table 7.1 Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Synergistic effects of pollution reduction and carbon mitigation in energy transition	351	58 445	166.51	2016.9
2	AI-driven sustainable water treatment technology	51	4 124	80.86	2021.4
3	Nanoconfinement-enhanced pollutant degradation technology	50	5 322	106.44	2020.9
4	Assessment of potential environmental and health risks from new particles	40	1 838	45.95	2021.8
5	Control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments	28	1 422	50.79	2019.1
6	Research on AI application in intelligent grid forecasting	153	17 525	114.54	2019.8
7	Data-driven optimization of high-resolution ocean numerical models	6	306	51.00	2020.5
8	Research on nanofiber materials for wound healing	585	69 514	118.83	2020.6
9	Risk assessment and control of emerging contaminants in food	311	35 131	112.96	2019.3
10	Non-food biomass liquid fuels	18	474	26.33	2019.7

Table 7.2 Annual number of core papers published for the Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Synergistic effects of pollution reduction and carbon mitigation in energy transition	34	37	41	54	37	12
2	AI-driven sustainable water treatment technology	0	0	9	21	15	6
3	Nanoconfinement-enhanced pollutant degradation technology	0	0	21	16	8	5
4	Assessment of potential environmental and health risks from new particles	0	0	3	12	13	12
5	Control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments	11	10	3	2	2	0
6	Research on AI application in intelligent grid forecasting	28	34	47	31	5	8
7	Data-driven optimization of high-resolution ocean numerical models	1	0	2	1	2	0
8	Research on nanofiber materials for wound healing	22	59	176	189	119	18
9	Risk assessment and control of emerging contaminants in food	89	81	72	35	23	1
10	Non-food biomass liquid fuels	6	4	2	2	4	0

across intersecting disciplines, specifically by intensifying cooperation between environmental science, energy studies, and economics to establish a more sophisticated theoretical guidance system bolstered by quantitative supports. Simultaneously, constructing a data resource sharing platform is imperative to elevate the transparency and verifiability of research outcomes, thus expediting the translation of knowledge into practical applications. Additionally, the development and application of new technologies will be decisive in determining the effectiveness of energy transition, exemplified by cost reductions and efficiency enhancements in novel energy technologies, comprising advances in energy storage systems, hydrogen economy, and ongoing improvements in carbon capture and storage technologies. Complementarily, the maturation of emerging information technologies, such as AI and the Internet of Things, plays a pivotal role in this endeavor.

(2) AI-driven sustainable water treatment technology

AI-driven sustainable water treatment technologies leverage AI to enhance the efficiency and sustainability of water treatment processes. By employing machine learning and deep learning algorithms, these technologies extract actionable insights from complex water quality datasets, facilitating the identification of pollution sources, forecasting water quality variations, and optimizing treatment methodologies. Key research areas include intelligent monitoring and data analytics, process optimization and control, fault prediction and preventive maintenance, as well as pollution source identification and management. AI technologies analyze data from distributed sensor networks to provide real-time monitoring of water quality parameters, delivering precise assessments and early warnings. They optimize critical parameters within the treatment process, predict equipment failure risks through operational data analysis, and recommend preventive maintenance strategies. Furthermore, AI aids in identifying pollution sources within intricate aquatic systems, analyzing pollutant migration and transformation pathways, and proposing effective control and remediation strategies. By integrating AI's robust data processing and analytical capabilities with practical water treatment applications, these technologies enable AI to undertake the majority of monitoring, control, and analytical tasks. This integration significantly enhances resource utilization, reduces waste emissions, and advances water treatment efficiency, cost-effectiveness, and environmental impact mitigation.

(3) Nanoconfinement-enhanced pollutant degradation technology

Nanomaterials exhibit the quantum size effect, small size effect, surface effect, and macroscopic quantum tunneling effect,

which result in high surface activity and catalytic efficiency, as well as rapid chemical reaction kinetics, attracting wide attention in the fields of pollutant treatment. When the size is limited to within one or several nanometers, the phase behavior of the material, as well as the energy distribution of chemical reactions or physical processes, may differ from its macroscopic properties—this is known as the nanoconfinement effect. Nanoconfinement can increase the material's specific surface area, the density and activity of surface sites, change the characteristics of electron motion, leading to significant changes in the thermodynamic and kinetic properties of chemical reactions. This produces reaction pathways and results that are significantly different from those in the bulk phase. The nanoconfined space provides conditions for the generation and stable existence of many thermodynamically unstable crystal phases, and also provides microscopic spaces for the rapid diffusion and enrichment of trace pollutants and free radicals, such as increasing the content of hydroxyl radicals and singlet oxygen, accelerating the mass transfer of active species and pollutants, and thereby enhancing pollutant degradation. At the same time, the surface of the confined space interacts with the adsorbent material, altering the electronic spin mode and enhancing the binding strength between the adsorbent material and the pollutant, greatly improving the pollutant degradation rate. Currently, nanoconfinement-enhanced pollutant degradation technology mainly focuses on enhancing wastewater treatment performance, improving the activity and stability of catalysts, and understanding the degradation kinetics process. It has been applied in the fields of water treatment and catalysis, such as the confined Fenton reaction in advanced oxidation water treatment process, which has a reaction kinetics 820 times higher than that of the unconfined Fenton reaction. However, nanoconfinement-enhanced pollutant degradation technology still faces challenges. In the future, it is necessary to deeply understand the reaction mechanism and kinetics within the nanoporous structure, improve the life and stability of nanoconfined materials to support the efficient removal of pollutants.

(4) Assessment of potential environmental and health risks from new particles

New particle formation (NPF) refers to the sophisticated process through which ultrafine particles—typically under 100 nanometers in diameter—are generated in the atmosphere via gas-phase chemical reactions, condensation, and various physical phenomena. These emergent particles are largely formed through gaseous precursors, including volatile organic compounds, sulfur dioxide, and ammonia, which condense under specific environmental conditions. The advent of new particles holds significant implications for atmospheric chemistry, climate systems, and public health. As urbanization and industrialization intensify, the concentration of these particles has markedly increased, rendering NPF a pivotal focus of contemporary air pollution research.

Currently, research on new particles focuses on analyzing exposure levels among different populations both regionally and globally, exploring their sources, concentration distributions, and variation patterns. This involves integrating monitoring data with predictive models to quantify individual exposure levels and reveal the generation mechanisms of new particles at both regional and global scales. Some studies conduct regional and global epidemiological surveys to uncover the associations between various types of new particles and their concentrations with respiratory diseases, cardiovascular diseases, and other health issues, particularly their impact on susceptible populations. Additionally, research investigates the dominant effects of different types of new particles on health in various regions, as well as the influence of long-term exposure on chronic disease incidence, using animal and cellular models to explore the potential hazards and pathological mechanisms associated with new particles.

In the future, we should proactively enhance the utilization of advanced big data models and machine learning techniques to conduct in-depth analyses of health data pertaining to novel particles, with the objective of improving the accuracy and efficiency of risk assessments. Concurrently, we should leverage automation and high-throughput measurement technologies to engineer environmental online monitoring systems, facilitating rapid screening and evaluation of the biological health effects associated with new particles, alongside real-time monitoring of exposure levels and their health repercussions. Moreover, it is essential to develop innovative models to evaluate the health risks linked to exposure to these new particles, incorporating strategies for risk prediction and management. Additionally, research into the synergistic interactions between new particles and other pollutants should be expanded, proposing integrated control strategies for collaborative pollution mitigation.

(5) Control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments

Deep-sea REY-rich sediments refer to sediments rich in rare earth elements (lanthanides and yttrium) formed in deep-sea environments, representing a potential new source of rare earth resources. Existing surveys have identified several prospective mineralization belts for REY; however, the mechanisms controlling the extraordinary enrichment of REY in deep-sea environments have not been fully elucidated.

Current research on the mechanisms controlling the extraordinary enrichment of deep-sea REY primarily focuses on the following technological directions and development trends. ① REY enrichment carriers: The application of micro-area analytical techniques has confirmed that biogenic phosphates and iron-manganese micro-nodules are significant carriers for REY enrichment. Future studies should enhance the investigation of smaller-scale and diverse types of REY enrichment carriers. ② REY cycling during diagenesis: It is known that iron-manganese micro-nodules can release REY during diagenesis due to changes in redox conditions. Further research is needed to understand the adsorption capacity of carrier particles such as biogenic phosphates and the migration processes of REY during diagenetic alteration. ③ Regional factors affecting extraordinary REY enrichment: There are differences in the sources, types, and abundances of REY in various tectonic regions. It is essential to advance the study of the primary environmental factors controlling local extraordinary REY enrichment. ④ Temporal factors in extraordinary REY enrichment: The application of integrated dating methods and extensive stratigraphic correlation studies will help reveal the geological epochs during which deep-sea REY-rich sediments were formed.

(6) Research on AI application in intelligent grid forecasting

Artificial intelligence (AI) refers to an intelligent system created by humans, capable of performing complex tasks. AI involves multiple fields such as computer science, mathematics, and statistics, aiming to realize functions such as machine self-learning, reasoning, perception, and planning through simulation and extended intelligence. The application of AI in intelligent grid forecasting is a rapidly developing field. It utilizes machine learning and deep learning techniques to improve the accuracy and efficiency of weather forecasting, transforming sparse and dispersing point-based forecasts into seamless, fully covered, and refined grid digital forecasts. This enhances forecast accuracy, enriches forecast content, and provides more scientific and reliable data support for disaster prevention and reduction, public services, and industry services. Current key applications and research directions include: ① massive data processing and feature analysis; ② model optimization and forecast correction; ③ forecasting and prediction modeling; ④ dynamic updates and feedback mechanism; ⑤ visualization and interpretability. With the continuous development of AI technology and the expansion of application scenarios, the intelligent grid forecasting system will play a more important role in the future. On the one hand, AI will integrate more deeply with numerical forecasting and big data mining applications to develop more complex and accurate forecasting models and methods. On the other hand, the intelligent grid forecasting system will continue to expand its service areas and application scenarios, providing more comprehensive and refined meteorological services for the public and industry.

(7) Data-driven optimization of high-resolution ocean numerical models

The parameterization scheme of ocean circulation models simplifies ocean dynamic processes that occur at scales lower than the model grid resolution through the use of statistical methods. The choice of parameterization scheme significantly influences the simulation capability and predictability of ocean models. Consequently, parameter tuning is a critical step in setting up ocean numerical models.

Currently, the optimization of parameters in ocean circulation models is primarily conducted manually, relying on the modeler's experience. This approach lacks theoretical grounding and systematic engineering methods, making the optimization process complex, tedious, repetitive, and inefficient. Machine learning can extract patterns from vast observational data and establish new parameterization schemes, thereby enhancing the simulation capability and predictability of ocean models. This technique offers opportunities for optimizing parameterization schemes in ocean numerical models. During the optimization of ocean model parameters, the computational power of modern supercomputers can be utilized to simulate a wide range of parameter sets. By comparing these simulations with observational data, a sample set of model inputs and a sample set of optimal physical

parameters can be created. This approach will facilitate the development of a machine learning model that links model inputs to the most effective parameterization schemes. When employing the ocean model for simulation and prediction, optimal parameter values can be derived to enhance the simulation accuracy and improve predictability. The machine learning method integrates advanced computing technology with marine scientific research. It is anticipated that this approach will significantly enhance the simulation capabilities and forecast accuracy of ocean models in the future.

(8) Research on nanofiber materials for wound healing

The study of nanofiber materials in wound healing is becoming an important branch of biomedical materials science. Nanofibers, usually referred to as fibers with diameters in the nanometer scale, have been widely studied for promoting wound healing and tissue regeneration due to their unique high specific surface area, high porosity, and microstructure that can mimic the extracellular matrix. These materials, prepared by using electrospinning technology, can precisely control the diameter and alignment of fibers, modulating cell adhesion, and proliferation and differentiation behaviors.

Current major research directions include the structural design, surface modification, drug release systems, and biocompatibility evaluation of nanofibers. Through novel nanofiber preparation processes, such as coaxial electrospinning and multi-axial electrospinning, researchers have achieved the encapsulation and controlled release of drugs and bioactive molecules, promoting wound healing, reducing scar formation, and preventing infection. Surface modification of nanofibers is also a hot research topic. By modifying the surface of nanofibers using physical or chemical methods, antimicrobial, hydrophilic, and cell adhesion properties can be enhanced.

Future development trends will focus more on the multifunctional integration of nanofiber materials, such as combining photothermal therapy, photodynamic therapy, and smart response materials to achieve real-time responses to the complex wound environment and precise treatment. Additionally, with the development of portable electrospinning devices, on-site preparation and application of nanofibers will become feasible, providing new solutions for outdoor wound management and battlefield medicine. Furthermore, research on nanofiber materials will emphasize clinical translation, accelerating the clinical application and industrialization of novel wound healing materials through close integration with clinical medicine.

(9) Risk assessment and control of emerging contaminants in food

Emerging contaminants in food mainly include antibiotics, endocrine disruptors, perfluorinated compounds, microplastics, and other contaminants that transfer to food from soil, water, air and other environmental factors. Emerging contaminants cause serious negative impacts on food quality and safety after entering the food chain. In the food sector, food safety issues caused by emerging contaminants are widespread and continuously affect food safety supply.

Emerging contaminants are numerous varieties with various properties, and the food chain and food matrix are complex. Therefore, it is of great significance to complete safety supervision and risk assessment of emerging contaminants in food by conducting the following research: exploring the chemical structures and properties of emerging contaminants; developing and establishing high-precision and sensitive detection methods to achieve rapid and accurate identification of emerging contaminants in food; exploring the migration and transformation laws of emerging contaminants from the environment to food and throughout food production, processing, storage, and consumption; investigating the stability and interactions of emerging contaminants in the food matrix. Additional hot research topics include clarifying the exposure amounts and paths of emerging contaminants; establishing the dose-effect relationship between emerging contaminants in food and specific groups (such as infants, pregnant women, the elderly, and those with chronic diseases) and exploring their hazard mechanisms. Building a risk assessment big data platform that integrates data collection, processing, analysis, and early warning of emerging contaminants is also an important research direction.

(10) Non-food biomass liquid fuels

The transformation of the global energy mix and the requirements for environmental protection have driven the development of renewable energy. Biomass energy, an important part of renewable energy, is both environmentally

friendly and resource-abundant. Among the numerous biomass feedstocks available in nature, adopting non-food biomass as raw material can effectively alleviate competition between food and fuel, avoiding impacts on food security. Additionally, the conversion of agricultural and forestry wastes into usable fuels contributes to a circular economy and efficient resource utilization. Non-food biomass liquid fuels are a significant category of non-food biomass energy, referring to liquid fuels derived from non-food biomass resources (such as agricultural waste, forestry by-products, and municipal waste) through physical, chemical, or biological conversion. These fuels include bioethanol, sustainable aviation fuel, green methanol, and biodiesel. However, the development of non-food biomass liquid fuels still faces challenges such as low energy density, high feedstock costs, and unstable feedstock supply. In the future, research on non-food biomass liquid fuels should focus on the following aspects: ① optimizing the feedstock conversion process to increase conversion efficiency and yield; ② developing new catalysts and reaction conditions to reduce production costs and improve product quality; ③ improving pretreatment technologies for biomass feedstocks to further enhance conversion efficiency; ④ exploring diversified applications of liquid fuels (such as their extensive utilization in transportation, power generation and heating) to boost market maturity and promotion.

7.1.2 Interpretations for three key engineering research fronts

7.1.2.1 Synergistic effects of pollution reduction and carbon mitigation in energy transition

The world currently faces dual pressing challenges: addressing climate change and controlling air pollution. The former focuses on reducing greenhouse gases like CO₂ to slow global warming, while the latter targeting pollutants such as PM_{2.5}, SO₂, NO_x to improve air quality and protect ecosystems and human health. Against the backdrop of energy transition, significant synergy is observed between these two efforts. The shift from traditional fossil fuels to clean energy can simultaneously decrease air pollutants and reduce carbon emissions.

Research on the synergy between air pollution reduction and carbon mitigation during energy transition exhibits a distinct cross-disciplinary nature. For instance, assessing the synergy requires consideration of both direct and indirect links between greenhouse gases and pollutants, along with a quantification of not only their environmental benefits but also their economic, health, and multi-dimensional benefits. This requires integration across fields such as economics, energy, environment, and medicine, as well as consideration of interactions among various modules. Consequently, the complexity of data requirements, modeling, and problem-solving is increased.

In terms of core research outputs (Table 7.3), China leads in this field, with the highest number of core papers, accounting for 44.73% of global outputs. The USA ranks second in terms of core paper numbers. Among the top ten institutions (Table 7.4), the first six come from China, with Tsinghua University leading with 16 core papers and a 4.56% share of total papers, followed by Beijing Institute of Technology and Peking University. The remaining institutions in the top ten have similar core paper outputs, while King Abdullah University and University of Science and Technology of China have the highest citations per paper.

In terms of international cooperation among countries and institutions (Figures 7.1 and 7.2), research on the synergy between air pollution reduction and carbon mitigation during energy transition displays distinct international collaboration features, especially among China, the USA, and their collaborations with other countries. The pattern of institutional collaboration is also apparent, with Beijing Institute of Technology and King Abdullah University mainly conducting independent research, while Tsinghua University and other institutions have more frequent collaborative relationships. The citations per paper, used as an indicator of paper influence, may be somewhat limited because it does not exclude self-citations. Countries and institutions with the greatest output of citing papers are shown in Tables 7.5 and 7.6. Figure 7.3 shows the roadmap of the engineering research front of “synergistic effects of pollution reduction and carbon mitigation in energy transition”.

Table 7.3 Countries with the greatest output of core papers on “synergistic effects of pollution reduction and carbon mitigation in energy transition”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	157	44.73	24 935	158.82	2019.3
2	USA	63	17.95	11 585	183.89	2015.2
3	UK	31	8.83	6 823	220.10	2016.3
4	Malaysia	26	7.41	4 000	153.85	2018.2
5	Turkey	24	6.84	5 158	214.92	2016.2
6	Australia	23	6.55	3 871	168.30	2018.7
7	Pakistan	23	6.55	3 494	151.91	2020.7
8	India	23	6.55	3 459	150.39	2017.3
9	Saudi Arabia	16	4.56	3 196	199.75	2019.8
10	Italy	14	3.99	1 875	133.93	2015.8

Table 7.4 Institutions with the greatest output of core papers on “synergistic effects of pollution reduction and carbon mitigation in energy transition”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Tsinghua University	16	4.56	2 007	125.44	2018.4
2	Beijing Institute of Technology	12	3.42	1 624	135.33	2020.2
3	Peking University	10	2.85	1 390	139.00	2018.6
4	Chinese Academy of Sciences	10	2.85	1 230	123.00	2016.0
5	Zhengzhou University	9	2.56	1 238	137.56	2020.1
6	University of Science and Technology of China	7	1.99	1 927	275.29	2018.4
7	International Institute for Applied Systems Analysis	7	1.99	671	95.86	2016.9
8	University of California, Berkeley	6	1.71	869	144.83	2012.2
9	Cyprus International University	6	1.71	677	112.83	2021.8
10	King Abdulaziz University	5	1.42	1 716	343.20	2018.8

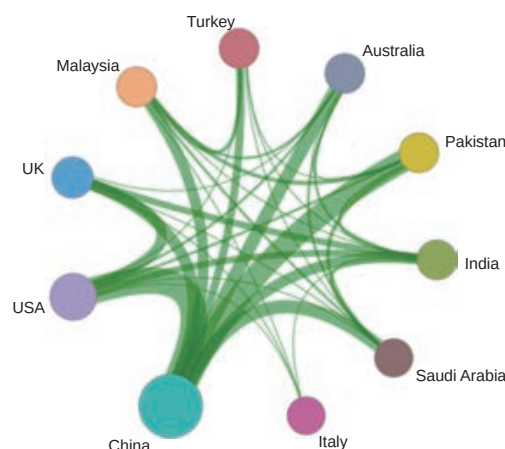


Figure 7.1 Collaboration network among major countries in the engineering research front of “synergistic effects of pollution reduction and carbon mitigation in energy transition”

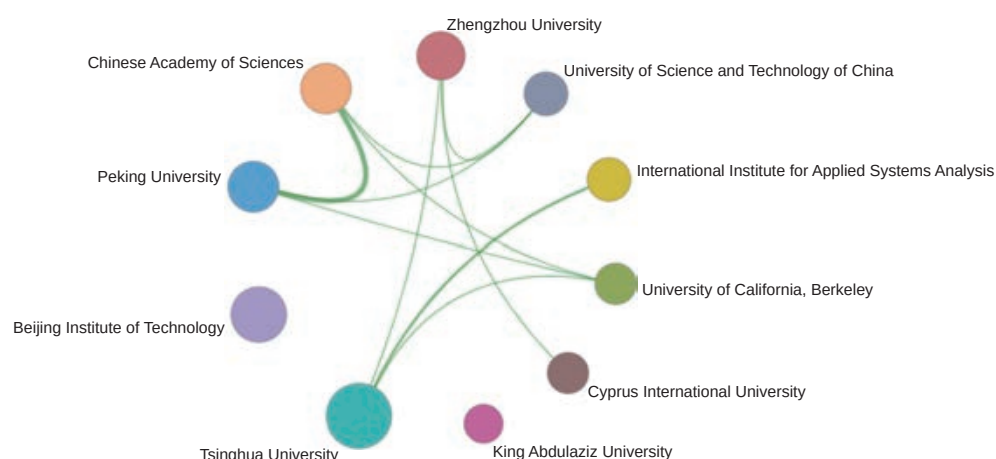


Figure 7.2 Collaboration network among major institutions in the engineering research front of “synergistic effects of pollution reduction and carbon mitigation in energy transition”

Table 7.5 Countries with the greatest output of citing papers on “synergistic effects of pollution reduction and carbon mitigation in energy transition”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	212	31.09	2017.6
2	USA	128	18.77	2015.1
3	UK	58	8.50	2014.8
4	Australia	47	6.89	2016.9
5	Germany	39	5.72	2016.4
6	Turkey	38	5.57	2014.1
7	Spain	37	5.43	2015.2
8	Saudi Arabia	36	5.28	2015.8
9	India	35	5.13	2015.6
10	Canada	26	3.81	2015.9

Table 7.6 Institutions with the greatest output of citing papers on “synergistic effects of pollution reduction and carbon mitigation in energy transition”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Wuhan University of Technology	33	18.64	2017.6
2	Chinese Academy of Sciences	28	15.82	2016.9
3	Tsinghua University	22	12.43	2016.8
4	King Abdulaziz University	20	11.30	2016.5
5	University of Science and Technology of China	12	6.78	2016.2
6	South China Agricultural University	11	6.21	2017.5
7	University of Leeds	11	6.21	2016.6
8	University of California, Berkeley	11	6.21	2013.5
9	Beijing Institute of Technology	11	6.21	2019.5
10	National University of Malaysia	10	5.65	2014.1

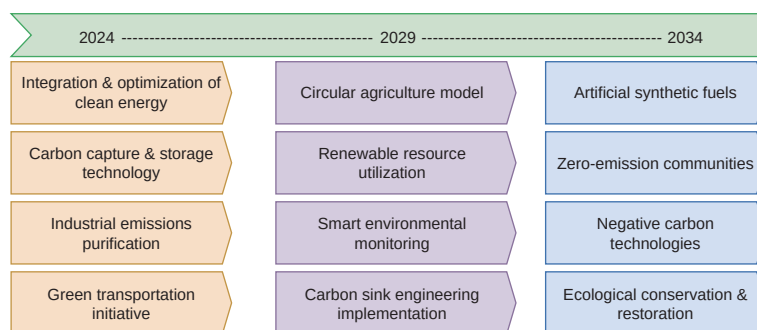


Figure 7.3 Roadmap of the engineering research front of “synergistic effects of pollution reduction and carbon mitigation in energy transition”

7.1.2.2 Control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments

With the rapid development of green energy and emerging industries, the demand for rare earth elements (lanthanides and yttrium, REY) continues to grow. Deep-sea REY-rich sediments, as a potential new source of REY, are receiving increasing attention. Currently, four prospective REY mineralization belts have been identified: the Western Pacific, Central-Eastern Pacific, Southeastern Pacific, and the Central Indian Ocean-Wharton Basin deep-sea REY mineralization belt. Ongoing research into the extraordinary enrichment mechanisms of deep-sea REY will enhance exploration efficiency and provide foundational support for the development of this future industry.

The main research directions for understanding the control mechanisms of extraordinary REY enrichment in deep-sea environments include: ① REY enrichment carriers. The application of micro-area analytical techniques has confirmed that biogenic apatite and iron-manganese micro-nodules are significant carriers of REY. Further research is needed to explore the REY enrichment capabilities of smaller-scale and diverse types of carrier particles; ② Cycling of REY in the process of diagenesis. Micro-area analysis, leaching experiments, physical simulation, and other means are widely used to reveal the cycling process of REY under different diagenesis conditions; ③ Geographical factors of extraordinary REY enrichment. There are differences in the sources of REY, the types and abundances of REY carriers in mid-ocean ridges, seamounts, and abyssal plains. The roles of local factors and environmental variables in the extraordinary enrichment of REY are not yet clear, so related research needs to be promoted; ④ Temporal factors of extraordinary REY enrichment. The development of specific dating techniques, enrichment experiments, the application of comprehensive dating tools, and extensive comparative stratigraphic studies will help reveal the time and era of the formation of deep-sea REY-rich sediments.

Among the major output countries of core papers in this research front (Table 7.7), China dominates this research field with the highest number of core papers. The USA is second in terms of the number of core papers, but has the highest citations per paper. In terms of the cooperation network of major output countries (Figure 7.4), China, the USA, and Germany have relatively close cooperation in this research area. In terms of major output institutions (Table 7.8), eight of the top ten institutions are from China, with Sun Yat-sen University leading with six core papers and 21.43% of papers, followed by Guangzhou Marine Geological Survey and Chinese Academy of Sciences. In the cooperation network among major institutions (Figure 7.5), Sun Yat-sen University, Guangzhou Marine Geological Survey, Chinese Academy of Sciences, and Key Laboratory of Marine Resources and Coastal Zones of Guangdong Province show frequent cooperation in this research field. Additionally, in terms of the countries with the greatest output of citing papers (Table 7.9), China leads with 609 citing papers and a proportion of 40.04%. Among the institutions with the greatest output of citing papers (Table 7.10), the Chinese Academy of Sciences is ahead with 198 citing papers and a proportion of 28.21%. In conclusion, for the research of this front, China holds an advantageous position in this field, and the cooperation among domestic institutions is relatively close, but further cooperation with international institutions is needed to enhance the global impact of its research. Figure 7.6 shows the roadmap of the engineering research front of “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”.

Table 7.7 Countries with the greatest output of core papers on “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	16	57.14	675	42.19	2019.6
2	USA	8	28.57	622	77.75	2018.4
3	Germany	5	17.86	365	73.00	2019.4
4	Australia	2	7.14	96	48.00	2020.0
5	Switzerland	2	7.14	79	39.50	2018.0
6	Japan	1	3.57	50	50.00	2019.0
7	France	1	3.57	48	48.00	2018.0
8	Norway	1	3.57	48	48.00	2018.0
9	UK	1	3.57	48	48.00	2018.0
10	Netherlands	1	3.57	38	38.00	2018.0



Figure 7.4 Collaboration network among major countries in the engineering research front of “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

Table 7.8 Institutions with the greatest output of core papers on “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Sun Yat-sen University	6	21.43	277	46.17	2020.0
2	Guangzhou Marine Geological Survey	5	17.86	246	49.20	2020.0
3	Chinese Academy of Sciences	5	17.86	178	35.60	2019.8
4	Key Laboratory of Marine Resources and Coastal Zones of Guangdong Province	4	14.29	216	54.00	2019.5
5	Nanjing University	4	14.29	210	52.50	2019.2
6	Constructor University	3	10.71	279	93.00	2020.3
7	China University of Geosciences	3	10.71	133	44.33	2019.0
8	Qingdao National Laboratory for Ocean Science and Technology	3	10.71	110	36.67	2020.0
9	Ministry of Natural Resources	3	10.71	106	35.33	2021.0
10	United States Geological Survey	2	7.14	269	134.50	2019.0

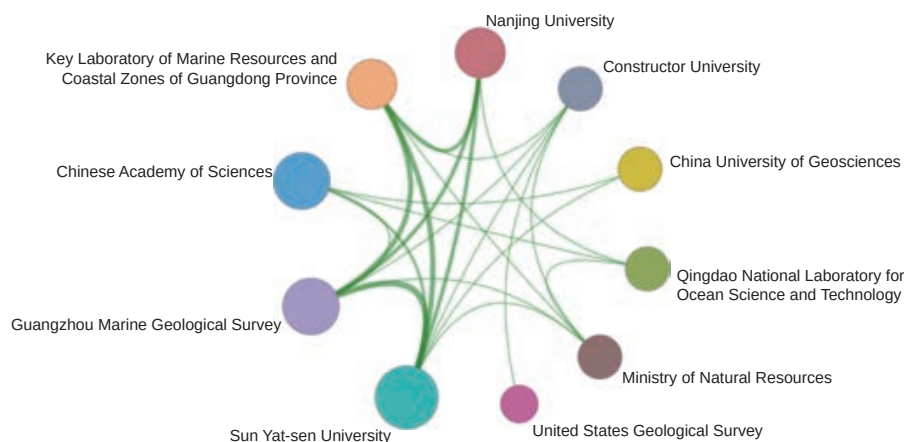


Figure 7.5 Collaboration network among major institutions in the engineering research front of “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

Table 7.9 Countries with the greatest output of citing papers on “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	609	40.04	2021.9
2	USA	257	16.90	2021.5
3	Germany	101	6.64	2021.7
4	UK	99	6.51	2021.5
5	Australia	91	5.98	2021.5
6	Canada	90	5.92	2021.5
7	France	66	4.34	2021.3
8	Japan	65	4.27	2021.7
9	India	56	3.68	2021.4
10	Switzerland	51	3.35	2021.0

Table 7.10 Institutions with the greatest output of citing papers on “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	198	28.21	2021.9
2	China University of Geosciences	126	17.95	2021.7
3	Chinese Academy of Geological Sciences	65	9.26	2021.9
4	Ministry of Natural Resources (China)	63	8.97	2022.2
5	China Geological Survey	50	7.12	2022.0
6	University of Tokyo	42	5.98	2021.5
7	Nanjing University	36	5.13	2021.5
8	Chiba Institute of Technology	32	4.56	2021.5
9	ETH Zurich (Swiss Federal Institute of Technology in Zurich)	30	4.27	2020.6
10	Chengdu University of Technology	30	4.27	2022.1

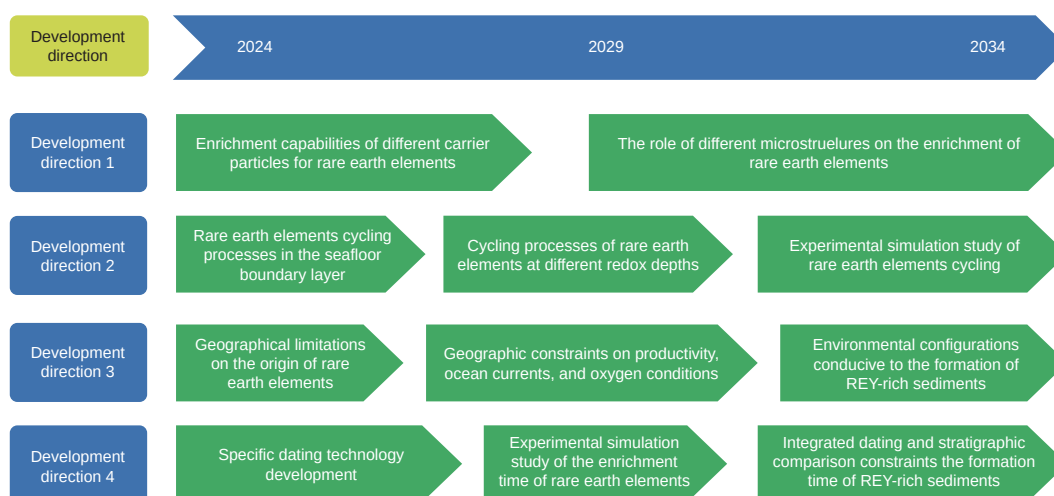


Figure 7.6 Roadmap of the engineering research front of “control mechanisms of extraordinary enrichment of rare earth elements in deep-sea environments”

7.1.2.3 Research on nanofiber materials for wound healing

The study of nanofiber materials for wound healing is a current research frontier in the field of textile biomedical materials, with significant scientific importance and promising application prospects. Research in this field focuses on developing novel nanofiber materials to facilitate wound healing, improve therapeutic efficacy, reduce patient pain, and decrease healthcare costs.

Nanofiber materials have become a hotspot in wound healing research due to their unique physicochemical properties, such as high specific surface area, excellent mechanical properties and tunable pore structure. Recent advancements in nanotechnology and materials science have led to significant progress in the application of nanofiber materials in wound dressings, drug delivery systems, and tissue engineering scaffolds. Research trends indicate that the field will pay more attention to the biocompatibility, bioactivity and intelligent response ability of materials in the future.

Wound healing is a complex biological process involving the interaction of multiple cell types and signaling molecules. Nanofiber materials can mimic the microstructure of the extracellular matrix and provide a conducive environment for cell attachment and growth, thus promoting wound healing. In addition, nanofiber materials can be loaded with drugs and growth factors to regulate the wound healing process and improve therapeutic outcomes.

Main research directions include: ① Preparation and characterization of nanofibers: Studying the effects of different polymers and preparation methods on the morphology, structure, and properties of nanofibers. ② Biocompatibility and bioactivity: Assessing the compatibility of nanofiber materials with organisms and their ability to promote cell growth and differentiation. ③ Drug delivery systems: Developing nanofiber-based drug carriers for controlled release and targeted delivery of drugs. ④ Tissue engineering scaffolds: Designing and preparing nanofiber scaffolds with good biocompatibility and mechanical properties for tissue repair and regeneration.

Countries and institutions with the greatest output of core papers on “research on nanofiber materials for wound healing” are shown in Tables 7.11 and 7.12. China, the USA, and Iran are the main output countries of research in this field, which indicates that these countries have strong scientific capabilities and active academic atmosphere in nanofiber materials research. Countries such as India, Egypt, Republic of Korea, and Malaysia also show active research dynamics in this field. Chinese Academy of Sciences and Xi'an Jiaotong University are leading research in this field, reflecting China's strong strength in nanofiber materials research. Other institutions such as Sichuan University, Qingdao University, and Shanghai University of Science and Technology have also made significant contributions in this field.

Collaboration networks show that there are increasing collaboration between countries/institutions, which helps promote

knowledge exchange and technological innovation (Figures 7.7 and 7.8). International cooperation enables the integration of research resources from different countries, accelerating the translation and application of research results. Countries and institutions with the greatest output of citing papers on this front are shown in Tables 7.13 and 7.14.

In the next 5–10 years, research on nanofiber materials for wound healing will focus on the following directions: ① Multifunctional integration: Developing nanofiber materials with multiple functions, such as antibacterial, antioxidant, and vascular regeneration. ② Intelligent response: Developing intelligent nanofiber materials that can respond to external stimuli (e.g., temperature, pH, and biomolecules). ③ Clinical translation: Strengthening clinical trials and applied research to promote the practical application of nanofiber materials in the medical field. ④ Mechanism studies: Investigating deeply the molecular mechanism and cellular level role of nanofiber materials in promoting wound healing (Figure 7.9).

In summary, nanofiber materials for wound healing represent a dynamic and promising research field, poised to significantly impact the medical and healthcare industry. With the emergence of new materials and technologies, future research will increasingly focus more on meeting clinical needs and improving patient experience to achieve more efficient and cost-effective wound treatment.

Table 7.11 Countries with the greatest output of core papers on “research on nanofiber materials for wound healing”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	311	53.16	41 989	135.01	2021.0
2	USA	95	16.24	11 917	125.44	2020.7
3	Iran	60	10.26	6 881	114.68	2020.3
4	India	41	7.01	4 372	106.63	2020.5
5	Egypt	25	4.27	2 698	107.92	2020.8
6	Republic of Korea	22	3.76	1 951	88.68	2020.8
7	Malaysia	20	3.42	2 430	121.50	2020.6
8	Singapore	18	3.08	1 974	109.67	2020.6
9	UK	16	2.74	1 765	110.31	2020.7
10	Australia	15	2.56	1 762	117.47	2021.0

Table 7.12 Institutions with the greatest output of core papers on “research on nanofiber materials for wound healing”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	42	7.18	6 230	148.33	2020.6
2	Xi'an Jiao Tong University	34	5.81	10 046	295.47	2021.3
3	Sichuan University	19	3.25	2 535	133.42	2021.0
4	Qingdao University	17	2.91	1 703	100.18	2021.4
5	University of Shanghai for Science and Technology	15	2.56	1 580	105.33	2021.1
6	Sun Yat-sen University	14	2.39	1 955	139.64	2021.4
7	Donghua University	14	2.39	1 442	103.00	2020.7
8	National University of Singapore	13	2.22	1 616	124.31	2020.5
9	Islamic Azad University	12	2.05	1 288	107.33	2020.3
10	Shanghai Jiao Tong University	11	1.88	1 314	119.45	2020.7

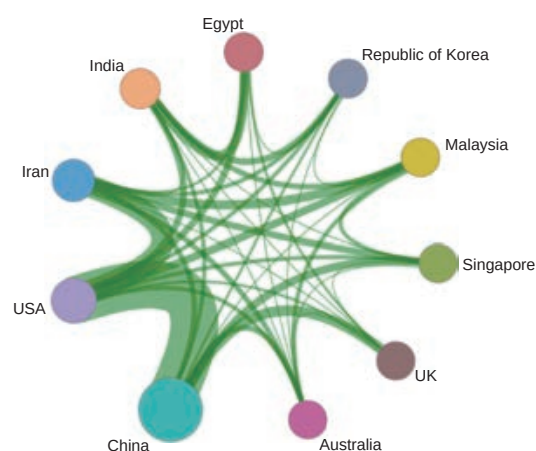


Figure 7.7 Collaboration network among major countries in the engineering research front of “research on nanofiber materials for wound healing”



Figure 7.8 Collaboration network among major institutions in the engineering research front of “research on nanofiber materials for wound healing”

Table 7.13 Countries with the greatest output of citing papers on “research on nanofiber materials for wound healing”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	289	49.32	2021.0
2	USA	85	14.51	2020.9
3	Iran	55	9.39	2020.5
4	India	36	6.14	2020.6
5	Egypt	23	3.92	2021.0
6	Republic of Korea	21	3.58	2020.9
7	Malaysia	18	3.07	2020.7
8	Singapore	16	2.73	2020.6
9	UK	15	2.56	2020.7
10	Canada	14	2.39	2020.8

Table 7.14 Institutions with the greatest output of citing papers on “research on nanofiber materials for wound healing”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	39	20.97	2020.8
2	Xi'an Jiao Tong University	32	17.20	2021.3
3	Sichuan University	19	10.22	2021.0
4	University of Shanghai for Science and Technology	14	7.53	2021.1
5	Sun Yat-sen University	14	7.53	2021.4
6	Qingdao University	13	6.99	2021.4
7	Donghua University	12	6.45	2020.8
8	Islamic Azad University	11	5.91	2020.4
9	National University of Singapore	11	5.91	2020.6
10	Nanjing University	11	5.91	2021.0

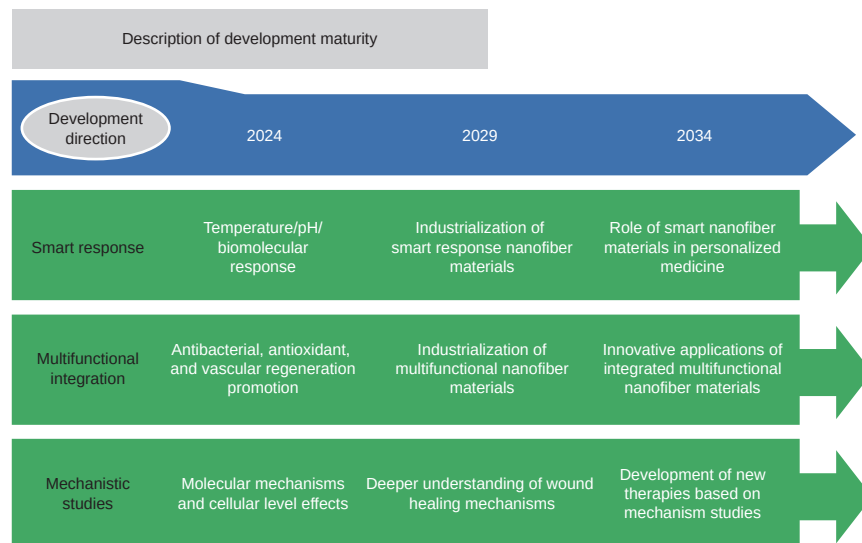


Figure 7.9 Roadmap of the engineering research front of “research on nanofiber materials for wound healing”

7.2 Engineering development fronts

7.2.1 Trends in the Top 10 engineering development fronts

The top ten engineering development fronts in the field of environmental and light textile engineering are summarized in Table 7.15, covering the subfields of environmental science, meteorological science, marine science, food science, textile science, and light industry science. The number of patents related to these individual topics between 2018 and 2023 is presented in Table 7.16.

(1) Low-maintenance decentralized water treatment technologies and equipment

Ensuring safe drinking water and effective wastewater management in rural areas is a key part of achieving the United Nations Sustainable Development Goals. However, remote rural areas often face challenges such as decentralized water sources, low

Table 7.15 Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Low-maintenance decentralized water treatment technologies and equipment	881	586	0.67	2020.8
2	Traceability and risk control of multi-media pollution based on big data mining	448	1426	3.18	2021.1
3	Carbon sequestration and storage construction materials	608	1438	2.37	2021.7
4	Technologies for dynamic monitoring and feedback of water quality for smart water treatment	821	1 771	2.16	2021.2
5	Application of intelligent models in the field of meteorology and oceanography	2	6	3.00	2022.5
6	Path planning technology for autonomous underwater vehicles based on deep reinforcement learning	120	1 489	12.41	2021.1
7	Application of digital twin technology in climate research	18	72	4.00	2022.7
8	Innovative utilization of novel food microbial resources	489	1 757	3.59	2021.5
9	Nano green printing technology	995	742	0.75	2021.0
10	Fiber-based solar cells	804	1 300	1.62	2020.3

Table 7.16 Annual number of core patents published for the Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Low-maintenance decentralized water treatment technologies and equipment	78	121	160	230	169	123
2	Traceability and risk control of multi-media pollution based on big data mining	45	49	55	86	108	105
3	Carbon sequestration and storage construction materials	39	35	35	82	173	244
4	Technologies for dynamic monitoring and feedback of water quality for smart water treatment	73	87	114	143	174	230
5	Application of intelligent models in the field of meteorology and oceanography	0	0	0	0	1	1
6	Path planning technology for autonomous underwater vehicles based on deep reinforcement learning	9	12	19	32	20	28
7	Application of digital twin technology in climate research	0	0	0	1	4	13
8	Innovative utilization of novel food microbial resources	28	40	65	85	92	179
9	Nano green printing technology	66	69	141	304	317	98
10	Fiber-based solar cells	164	147	128	118	129	118

pipeline coverage, and a lack of professional maintenance personnel, leading to outdated water treatment facilities and significant risks to drinking water safety, which also impacts water quality. Traditional centralized water treatment technologies often have limitations, such as lengthy processes, high chemical consumption, and complex management and maintenance. Therefore, developing low-maintenance, short-process water treatment technologies and equipment has become a key research focus in related engineering fields.

In recent years, decentralized drinking water purification technologies based on membrane technology have been widely promoted, including coagulation-submerged ultrafiltration and ultrafiltration-reverse osmosis. Compared to traditional water treatment processes, these methods offer better treatment efficacy, higher pathogen removal rates, shorter processes, and smaller land requirements, making them easier to install and avoiding complex construction processes. Current research directions for decentralized wastewater treatment include integrated membrane bioreactors, high-load biological filters, bio-disc systems, and constructed wetlands. Although these water treatment processes have proven effective in practical decentralized projects, their widespread application is still influenced by factors such as local water quality conditions, economic development, and technical management levels. To further enhance the capacity for decentralized water supply and drainage in rural areas, future technological trends include: ① developing in-situ dosing technologies and devices to reduce chemical consumption and maintenance workload; ② integrating AI to develop automated control programs, enhancing the intelligent operation of water treatment processes; ③ creating modular water treatment equipment to build prefabricated water plants; ④ establishing an evaluation system for decentralized water treatment technologies and equipment to promote standardized industry development.

(2) Traceability and risk control of multi-media pollution based on big data mining

Pollution traceability refers to the process of tracking and identifying the sources of environmental pollution and its diffusion paths through scientific methods and technical means. This process allows for the accurate analysis of pollution sources and migration paths, and is an important means to effectively carry out pollution remediation and risk control. At present, both domestic and international pollution traceability methods primarily rely on remote sensing technology, isotope technology, geochemical analysis, and pollution transport models. In the actual field of polluted land, pollutants from a wide range of sources and a variety of types of pollutants, different types of pollutants' migration and diffusion mechanisms are very different, and in the environmental media distribution of the randomness and uncertainty of the coupling conditions, the pollution source identification and control of the difficulty is greatly increased. Although at the present stage, it is common to use multi-technology joint means such as molecular fingerprinting technology combined with machine learning analysis to improve the accuracy of pollution traceability, but human-driven selection of technologies can result in significant differences in analysis results.

Big data mining technology forms a dataset by searching and integrating the required data, applies machine learning, deep learning, statistical analysis, and other technologies to comprehensively consider the pollution in multiple environmental media such as air, surface water, soil, and groundwater, and conducts pollution source tracking and risk assessment, and comprehensively analyses the impact and correlation between different data while ensuring the timeliness of the data to make up for the discrepancy and incompleteness of manual analyses. The huge amount of data can reveal potential pollution sources, predict pollutant diffusion paths and trends, and suggest more efficient and targeted control measures. However, the quality of the data obtained from big data mining and the judgment of different algorithms on the weight and relevance of the data will also lead to different analysis results. The development of multimedia pollution traceability and risk control based on big data mining is of great significance in solving the prevention and remediation of the complex situation of coupling of pollutants and existent media in the world, and it is also one of the important directions in the future research of environmental sciences and engineering, to ensure the accuracy of the data sources as well as the corrections to the data mining algorithms will be the research hotspot in this field.

(3) Carbon sequestration and storage construction materials

In 2022, the construction industry accounted for 37% of global carbon emissions related to energy and processes, amounting to nearly 100 billion tons. Concrete is the most widely used building material globally, and carbon can be sequestered and stored in concrete through the carbonation process after construction. Carbon sequestration in concrete can be achieved through carbonation strategies. Carbonation parameters such as initial carbonation conditions, carbonation duration, CO₂ pressure, source, and concentration can affect the effectiveness of carbon sequestration. The binder composition in concrete plays a crucial role in its carbon sequestration potential; the use of new aggregates in concrete can also enhance its ability to sequester carbon.

The optimal strategy for carbon sequestration and storage in concrete is to utilize the synergistic advantages of the materials and

methods introduced. However, there is still a lot of work to be done in determining the carbonation parameters, selecting binders, and developing new aggregates. These efforts are crucial for guiding the future of considering buildings as carbon sinks and meeting sustainable development goals.

(4) Technologies for dynamic monitoring and feedback of water quality for smart water treatment

Water treatment processes, including those for drinking water and wastewater, usually encounter fluctuations in influent and effluent water quality. Industrial wastewater treatment particularly experiences more frequent and significant water quality fluctuations. In traditional water treatment plants, operating staff often resort to measures like overdosing chemicals in response to water quality fluctuations to meet effluent quality standards, leading to increased operational costs and resource waste. In recent years, smart water treatment technologies, characterized by innovations in real-time monitoring, machine learning, dynamic feedback, model-based prediction and control, have rapidly emerged and developed. These technologies enable automatic control and optimization of water treatment processes. Through real-time monitoring and feedback mechanisms, parameters and processes could be dynamically adjusted based on water quality changes and demands, enhancing the water purification efficiency while reducing operational costs, minimizing resource and energy waste, and carbon emissions. Among these, the development of dynamic monitoring and feedback technologies plays a crucial role in supporting the implementation of smart water treatment. Key development directions include: ① technologies for rapid on-site monitoring of water quality indicators like biological oxygen demand (BOD) and trace contaminants of concern that traditionally require lengthy laboratory analysis, encompassing sensors, software, and automatic integrated equipment; ② technologies for rapid estimation and dynamic feedback of specific water quality indicators based on spectral measurement; ③ technologies leveraging machine learning and big data models for optimization and control of treatment operation parameters. China currently holds 88.5% of patents in this development frontier, demonstrating its role as a demand source, innovation hub, and primary market for these technologies.

(5) Application of intelligent models in the field of meteorology and oceanography

Intelligent models are AI-based computational models that can mimic human cognitive functions such as learning, reasoning, and pattern recognition, playing an important role in meteorology and oceanography fields. For example, in terms of weather forecasting, intelligent models can improve the accuracy of both short- and long-term weather forecasts, and help identify storm systems and other weather patterns more accurately. In terms of climate simulation, they can optimize climate models by accounting for factors such as atmosphere, oceans, and sea ice, to more accurately reproduce the real world. In terms of predicting extreme weather and climate events, they can identify the occurrence patterns of extreme weather and climate events (such as hurricanes and floods) and issue early warnings. In terms of marine current prediction, they can predict changes in ocean currents and help understand the diffusion of marine pollutants. In terms of marine ecosystems monitoring, they can extract information on sea surface temperature and salinity from remote sensing data and identify sound signals of marine organisms to help track the migration patterns of specific species. In terms of sea level rise, they can estimate the degree of possible sea level rise in the next few decades. In terms of marine pollution detection, they can be used to detect areas of marine pollution and assess their severity. Intelligent models promote the cross-integration of meteorology, oceanography, computer science, and other fields, deepening our understanding of Earth's systems. As technology advances and more data become available, intelligent models are expected to continue to optimize predictions in meteorology and oceanography fields, providing strong support for more accurate predictions and more efficient services.

(6) Path planning technology for autonomous underwater vehicles based on deep reinforcement learning

With the rapid development of underwater equipment technology, autonomous underwater vehicles (AUVs) have shown broad application prospects in fishery aquaculture, underwater rescue, marine environmental monitoring, marine biological surveys, and marine geological exploration. The complexity of marine environment requires safe and accurate path planning to ensure the efficient execution of AUV tasks. Deep reinforcement learning (DRL) has become the most promising method for AUV path planning in unknown dynamic environments because of its powerful perception and decision-making capabilities. The optimization and comprehensive utilization of DRL is a key issue to improve the autonomy and efficiency of AUV operation, which is of great

significance to help AUV ocean exploration and development reach the deep sea and promote the implementation of the strategy of maritime power.

At present, research on AUVs path planning technology based on deep reinforcement learning mainly include: improving DRL algorithm training speed and path planning accuracy; improving DRL algorithm's adaptability, real-time performance and robustness, and improving AUVs' global planning ability in unknown dynamic environments. The future development trend mainly includes the following aspects: First, breaking through the limitation of single AUV task execution, using deep reinforcement learning to plan the conflict-free operation path of AUV cluster, and improving the efficiency of multi-AUV collaborative operation. Second, expanding the multi-objective optimization capability of DRL algorithm to achieve effective path planning and long-term energy management under long-term or remote tasks. Third, carrying out the test and verification of the real equipment in real sea scenes, improving the adaptability of the DRL algorithm to complex environments, and escorting the underwater operation of AUVs.

(7) Application of digital twin technology in climate research

Digital twin refers to the combination of digital copies of physical objects or systems with their real-world counterparts through mathematical modeling, simulation, and data-driven technologies. The application of digital twin technology in climate research has emerged as an important development in recent years, mainly including the following aspects: ① Climate simulation: By constructing high-precision Earth models to simulate interactions between the atmosphere, oceans, land, and sea ice, providing detailed information on climate change. ② Prediction of extreme weather and climate events: through the analysis of historical data to identify the occurrence patterns of extreme weather and climate events and provide early warnings of potential natural disasters. ③ Climate change impact assessment: Evaluating the impacts of climate change on ecosystems, agriculture, water resources, and other aspects, as well as environmental issues caused by urbanization such as urban heat island effect and air quality. ④ Formulation of adaptation strategies: By simulating different climate change scenarios to develop adaptation strategies to mitigate negative impacts of climate change. ⑤ Smart agriculture: Creating virtual replicas of farmland to optimize irrigation, fertilization, etc.; adjusting operations based on real-time data to increase crop yields and reduce resource consumption. ⑥ Public education and awareness raising: Visualizing the potential impacts of climate change to the public and enhancing their understanding of environmental protection. In the future, digital twin technology will not only continue to deepen its integration with technologies such as AI and high-performance computing to promote the innovative development of climate research, but also promote international cooperation in climate research, advancing climate research progress and sharing of achievements.

(8) Innovative utilization of novel food microbial resources

The innovative utilization of novel food microbial resources combines microbiology, synthetic biology, and other advanced technologies to develop, optimize, and modify microorganisms used in food production. The aim is to enhance food's nutritional value, flavor, and safety. This technology extends beyond traditional fermentation to include genetic modification, metabolic regulation, and engineered microbial communities to improve food processing efficiency and create functional foods.

Key research areas include: ① fermentation technology innovation, using multi-strain co-fermentation and microbial community control to improve the taste and functionality of fermented foods; ② genetic editing and synthetic biology, employing tools like CRISPR to precisely modify microbial metabolic pathways for the production of specific functional ingredients such as prebiotics, bioactive peptides, and vitamins; ③ microecological regulation, using probiotics to modulate the gut microbiome, enhancing immunity and improving overall health; ④ green and sustainable development, where microorganisms transform agricultural waste into high-nutrient food, promoting green production systems and reducing resource waste.

In the future, food microbial technology will advance toward precision optimization, using genomics and proteomics to thoroughly analyze microbial functions for precise applications. Personalized functional foods will be developed based on individual microbiome characteristics. Smart fermentation technologies will integrate AI to optimize and control production processes. Additionally, green microbial technologies will be further integrated to support the sustainable development and ecological

transition of the food industry.

(9) Nano green printing technology

Printing technology is one of the four great inventions of ancient China, reflecting the developments and changes of human civilization. However, large amounts of pollutants (e.g., heavy metal ions, organic substances, and toxic gases) may be emitted during the conventional printing techniques based on photographic and etching processes, including plate production, printing plate making, and ink evaporation. This issue is detrimental to the sustainable development of the printing industry and inevitably causes environmental pollution. Additionally, the rise of electronic publishing has also put pressure and challenges on the conventional printing technology. Therefore, the transformation of printing technology is an inevitable trend for the development of the printing industry in China. Recently, researchers have applied nanotechnology to the plate, platemaking, and ink processes in printing technology, which not only addresses environmental pollution issues at the source but also enhances the level of modern printing technology. In the printing plate process, it is possible to achieve the wettability regulation during the printing process by coating a nano-functional layer on the plate surface to create special micro-nano structures, thus resolving issues like high energy consumption and serious pollution in conventional electrochemical processes such as electrolysis and oxidation. In the plate-making process, inorganic nanoparticles are utilized as transfer materials to print onto the surface of plates with micro-nano composite structures, avoiding the emission of photosensitive fluids. Furthermore, in the ink process, green inks are utilized to replace conventional solvent-based inks, thereby reducing VOC emissions during drying. Nano-green printing technology effectively addresses bottlenecks in conventional printing technology and can also expand to applications in the manufacture of new optoelectronic devices. In the future, there is still a need for further technological innovation and application research in printing accuracy, printing efficiency, and functionalization expansion, aiming to establish a complete industrial chain for nano green printing technology and ultimately transforming industrial technology.

(10) Fiber-based solar cells

Fiber-based solar cells are wearable energy devices that convert solar energy into electricity. These cells are typically based on flexible fiber or fabric structures, making them lightweight, bendable, and weavable. The core of such solar cells lies in the integration of photosensitive materials and electrodes into the fiber structure, enabling energy conversion and storage while maintaining textile comfort and wearability.

Current research focuses on improving the energy conversion efficiency, stability, and compatibility of fiber-based solar cells with textiles. Researchers are exploring different photosensitive materials, such as organic polymers, dye-sensitized materials, and chalcogenides, and their deposition techniques on fiber substrates. In addition, research is being conducted on how to enhance the mechanical stability and environmental adaptability of the cells through structural design and material selection.

Looking forward, future development trends will focus on integrating fiber-based solar cells with smart textiles to achieve multifunctionality and intelligence. For example, solar cells combined with sensors and electronic components could create smart garments that monitor health parameters, environmental conditions, or provide communication functions. In addition, advances in manufacturing technology will also make mass production and commercialization of fiber-based solar cells possible, further promoting the development of wearable energy devices.

7.2.2 Interpretations for three key engineering development fronts

7.2.2.1 Low-maintenance decentralized water treatment technologies and equipment

Over 3 billion people globally live in rural areas, many of which are economically disadvantaged. In some remote regions, drinking water sources are dispersed, pipeline coverage is low, and there is a lack of necessary water treatment facilities and professional maintenance personnel. Improving the safety of drinking water and wastewater treatment levels in rural areas is essential for safeguarding human health and social welfare. Developing low-maintenance technologies suitable for decentralized

water treatment scenarios, and achieving modularity and equipment standardization, is crucial for reducing operational and maintenance costs and meets significant engineering application needs.

To meet the demand for low-maintenance drinking water purification, membrane technology offers advantages such as high effluent quality, effective pathogen removal, short process flows, and ease of equipment standardization. For conventional surface water sources, coagulation-submerged ultrafiltration is employed to effectively remove organic matter, particulates, and microorganisms. For brackish water and groundwater with excessive inorganic pollutants like nitrates, ultrafiltration-reverse osmosis technology is generally used. In cases where only specific inorganic ions (such as arsenic, fluoride, iron, or manganese) are in excess, membrane processes can be bypassed, and coagulation/adsorption-sand filtration processes can be directly employed to reduce construction and operational costs. To address issues such as membrane fouling and high chemical consumption during operation, researchers have developed a prefabricated drinking water plant based on electrochemical-sand filtration/membrane technology, which generates flocculants and oxidants in situ through an electrochemical unit, combined with sand filtration and/or membrane units to achieve high-quality effluent while reducing membrane fouling.

For low-maintenance decentralized wastewater purification, current research focuses on biologically enhanced processes and equipment, including integrated membrane bioreactors, high-load biological filters, bio-disc systems, and constructed wetlands. Integrated membrane bioreactors combine activated sludge methods with membrane separation to increase activated sludge concentration, thereby enhancing the bioreactor's functionality and eliminating the need for secondary sedimentation tanks. This results in high-quality effluent and smaller land requirements. High-load biological filters and bio-disc systems utilize biofilm technology, where microorganisms are loaded onto the surface of the filter media to enhance microbial stability and reduce the impact of hydraulic load fluctuations. Constructed wetlands, an ecological water treatment technology, enhance pollutant degradation through the appropriate construction of soil and artificial medium structures, leveraging the roles of plants and microorganisms. This technology is easy to manage but requires a larger land area.

From an international perspective, among the major producing countries of core patents in “low-maintenance decentralized water treatment technologies and equipment” (Table 7.17), China ranks first, accounting for 99.55% of core patents published, demonstrating an absolute advantage compared to other countries like India and Germany, which have significantly fewer patent publications. This indicates that China's research and innovation in this field is continuously increasing, positioning it as a global leader.

In terms of the main institutions producing core patents in this front (Table 7.18), all of the top ten institutions are from China. Among them, Lingzhi Environmental Protection Co., Ltd. has the highest number of core patent publications, with 10 patents and citations per patent of 0.60, which is around the average level. Besides environmental companies, institutions like Chinese Research Academy of Environmental Sciences and South China Institute of Environmental Sciences have also contributed significantly to core patent output. However, the average citation data suggests that compared to research institutions, the influence and innovativeness of enterprises still require improvement. Additionally, there is minimal collaboration between these institutions. To elevate the research and application of related technologies, it is essential to strengthen the integration of industry, academia, and research institutions, and to develop a sustainable business model with diverse participation from the government, industry, and society, thereby promoting substantial development in relevant engineering technology fields.

Looking ahead to the development trends of low-maintenance decentralized water treatment technologies and equipment, future efforts should focus on strengthening research into membrane fouling control technologies and anti-fouling membrane materials, as well as developing low-maintenance, short-process membrane purification methods and equipment. For water supply and drainage scenarios in remote rural areas, there is a need to develop intelligent dosing and low/no chemical treatment technologies, while also emphasizing near-natural water purification techniques, processes, and supporting equipment development. Additionally, by integrating machine learning and 5G information technology, it is essential to develop digital simulation algorithms and platforms for water treatment processes, and to create unattended intelligent prefabricated water plants. This would enable real-time monitoring of operational conditions, online optimization of purification efficiency, remote control of process adjustments, and digital simulation for process upgrades, ensuring high-quality water supply and sustainable wastewater treatment in rural areas (Figure 7.10).

Table 7.17 Countries with the greatest output of core patents on “low-maintenance decentralized water treatment technologies and equipment”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	877	99.55	586	100.00	0.67
2	India	2	0.23	0	0.00	0.00
3	Germany	1	0.11	0	0.00	0.00
4	Ethiopia	1	0.11	0	0.00	0.00
5	Russia	1	0.11	0	0.00	0.00

Table 7.18 Institutions with the greatest output of core patents on “low-maintenance decentralized water treatment technologies and equipment”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Lingzhi Environmental Protection Co., Ltd.	10	1.14	6	1.02	0.60
2	Zhejiang Kangcheng Environmental Technology Co., Ltd.	9	1.02	1	0.17	0.11
3	China State Construction Engineering Corporation	8	0.91	0	0.00	0.00
4	Chinese Research Academy of Environmental Sciences	6	0.68	8	1.37	1.33
5	Power Construction Corporation of China	6	0.68	3	0.51	0.50
6	South China Institute of Environmental Sciences, Ministry of Ecology and Environment	5	0.57	9	1.54	1.80
7	Hubei Watsky Environmental Protection Engineering Co., Ltd.	5	0.57	6	1.02	1.20
8	Sichuan Academy of Eco-Environmental Sciences	5	0.57	5	0.85	1.00
9	Tongji University	5	0.57	4	0.68	0.80
10	Zhongling Water Environment Equipment	5	0.57	0	0.00	0.00

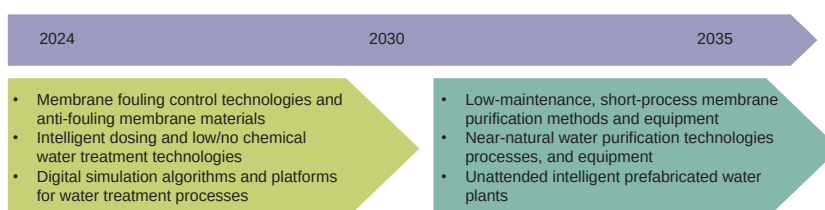


Figure 7.10 Roadmap of engineering development front of “low-maintenance decentralized water treatment technologies and equipment”

7.2.2.2 Application of intelligent models in the field of meteorology and oceanography

The application of intelligent models in the fields of meteorology and oceanography is increasingly extensive and in-depth, which significantly improves the accuracy and efficiency of meteorological prediction, and provides strong support for scientific research, environmental protection, disaster warning, and other aspects. The use of intelligent models in these fields dates back

to the early days of computer science and AI technology. Over time, these technologies have gradually developed and been introduced into the research and practice of meteorology and oceanography. At present, the development of intelligent models in meteorology and oceanography increasingly involves the cross-integration of multiple disciplines such as computer science, mathematics, and physics. Many countries have launched large-scale models in this field. For example, in the field of meteorology, the China Meteorological Administration has launched three AI weather modeling systems: “Fengqing”, “Fenglei”, and “Fengshun”. These systems enhance meteorological forecasting by integrating AI with meteorological knowledge. The global forecast reach of “Fengqing” model is 10.5 days, surpassing mainstream models in Europe and America. The “Fenglei” model significantly improves radar echo prediction capabilities. The “Fengshun” model focuses on solving the problem of long-term climate prediction, providing certainty and probability forecasts of global fundamentals and extreme events over the next 60 days. In the field of oceanography, the “14th Five-Year Plan” National Key Research and Development Project, led by the National Oceanic Information Center, has built six types of intelligent prediction models for sea surface temperature, sea surface height, three-dimensional thermohaline, ocean sound field, wave, and sea fog, as well as three types of intelligent identification models for mesoscale vortex, ocean front, and thermocline, achieving and lightweight intelligent prediction of the marine environment.

The main countries with the greatest output of core patents on “application of intelligent models in the field of meteorology and oceanography” are shown in Table 7.19. It can be found that only China has publicly released the number of core patents and the citations per patent, indicating that China has a strong research advantage in this area, but its international cooperation needs to be strengthened.

Table 7.20 shows the main output institutions for core patents in this engineering research front. The institution that has published the most core patents is North China Electric Power University, followed by Zhonghuan Yuen (Guangdong) Ecological Technology Co., Ltd. According to the main inter-agency cooperation network, it can be seen that there is no cooperation between the two leading domestic institutions.

The development of intelligent models in the fields of meteorology and oceanography over the next 5–10 years will be influenced by various factors, including technological advancements, improved computing power, increased data availability, and deepening interdisciplinary cooperation. Important development directions include: ① technological progress and model optimization; ② data processing and management mechanisms; ③ real-time and interactive forecasting; ④ application of digital twin technology; ⑤ interpretability and ethical issues; ⑥ interdisciplinary collaboration and open science; ⑦ education and public participation. With continuous technological advancements and increasing societal demands, the application of intelligent models in the fields of meteorology and oceanography is expected to become more extensive and in-depth (Figure 7.11).

Table 7.19 Countries with the greatest output of core patents on “application of intelligent models in the field of meteorology and oceanography”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	2	100.00	6	100.00	3.00

Table 7.20 Institutions with the greatest output of core patents on “application of intelligent models in the field of meteorology and oceanography”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	North China Electric Power University	1	50.00	5	83.33	5.00
2	Zhonghuan Yuen (Guangdong) Ecological Technology Co., Ltd.	1	50.00	1	16.67	1.00

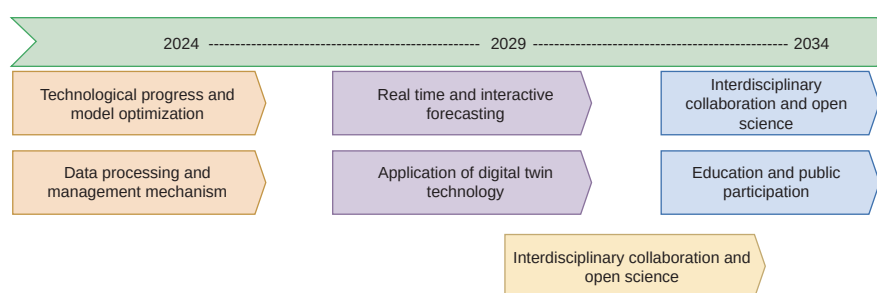


Figure 7.11 Roadmap of the engineering development front of “application of intelligent models in the field of meteorology and oceanography”

7.2.2.3 Innovative utilization of novel food microbial resources

Increasing consumer demand for health, nutrition, and food safety has driven the development of functional and personalized nutrition foods. Microorganisms, as producers of functional components such as prebiotics, bioactive peptides, vitamins, and amino acids, have significant application potential. By exploring and optimizing food microbial resources, it is possible to develop foods with high nutritional value and specific health benefits that meet the needs of modern consumers. Moreover, utilizing microorganisms can be utilized to convert low-value or waste materials into high-value nutritional products, offering a sustainable food production method that reduces resource waste and carbon emissions, aligning with global sustainability goals. Advances in modern “omics” technologies (genomics, metabolomics, proteomics, etc.) and bioinformatics have significantly enhanced the understanding of microbial functions, metabolic pathways, and ecosystems, making targeted microbial optimization and modification feasible.

As shown in Table 7.21, China and the Republic of Korea have demonstrated notable achievements in the patent output related to novel food microbial resource innovation in recent years, with the combined patent publication volume of these two countries accounting for 87.73% of the global total, far surpassing developed countries such as the USA, Japan, and France. Among these, China has published 193 patents, ranking second globally, just behind the Republic of Korea with 236 patents. In terms of citations, China leads globally with 688 citations, representing 39.16% of the total citations, significantly higher than the Republic of Korea’s 28.57%, indicating a higher recognition of China’s contributions to this field. However, China’s citation per patent of 3.56 is notably lower than that of countries like the USA, France, Denmark, and Italy, reflecting a relative lack of originality, depth of innovation, and technological impact in the field of novel food microbial resource utilization.

Regarding patent output institutions (Table 7.22), several Chinese institutions such as Jiangnan University and Inner Mongolia Yili Industrial Group Co., Ltd. rank among the top globally. However, the average citation frequency of their patents is generally low, indicating a need for greater technological impact. Figures 7.12 and 7.13 illustrate the cooperation networks among major countries and institutions in this technology area. It is evident that R&D collaboration between countries is relatively weak, with only a notable cooperation mainly occurring between the Republic of Korea and the USA. Inter-institutional cooperation is mainly concentrated within the Republic of Korea, such as between Korea Food Research Institute and Konkuk University, Korea Food Research Institute and CKD Bio Corporation, Korea Food Research Institute and Industry Foundation of Chonnam National University, and Korea Food Research Institute and Korea University Research and Business Foundation.

Overall, China should further strengthen international collaboration with other countries in the field of food microbial resource innovation, promote collaborative innovation between industry, academia, and research institutions, and enhance technological innovation capabilities. Additionally, it is crucial to move beyond a focus on quantity and optimize evaluation systems for research output quality and impact, encouraging research institutions to produce more internationally influential high-quality technologies and promote the sustainable development of related technologies and industries.

In the future, innovation and utilization of novel food microbial resources will focus on several key areas (Figure 7.14). Firstly, the development of functional foods will leverage microorganisms to produce beneficial components such as prebiotics, bioactive peptides, functional lipids, and antioxidants, enhancing health outcomes such as gut health, immunity, and chronic disease prevention. Personalized nutrition will be based on individual microbiome and genomic data to provide tailored dietary solutions that meet diverse health needs. Efficient microbial modification through synthetic biology and gene editing technologies (e.g., CRISPR) will enable the production of high-value food components, improving production efficiency and product functionality. Additionally, developing methods to use microorganisms to convert low-value or waste resources into high-value food and bio-products will promote sustainable development and resource efficiency.

As consumer demand for health and personalized foods increases, novel food microbial resource technologies will have broad application prospects. Technological advancements will enhance the precision and efficiency of microbial modifications, increasing the commercial value of these technologies. The innovative utilization of novel food microbial resources will achieve breakthroughs in functional foods, personalized nutrition, and sustainable production, driving modernization and sustainable development of the food industry.

Table 7.21 Countries with the greatest output of core patents on “innovative utilization of novel food microbial resources”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Republic of Korea	236	48.26	502	28.57	2.13
2	China	193	39.47	688	39.16	3.56
3	Japan	25	5.11	93	5.29	3.72
4	Denmark	7	1.43	124	7.06	17.71
5	Italy	5	1.02	68	3.87	13.60
6	USA	5	1.02	52	2.96	10.40
7	France	4	0.82	89	5.07	22.25
8	Netherlands	3	0.61	101	5.75	33.67
9	Poland	3	0.61	4	0.23	1.33
10	Switzerland	2	0.41	2	0.11	1.00

Table 7.22 Institutions with the greatest output of core patents on “innovative utilization of novel food microbial resources”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Korea Food Research Institute	40	8.18	48	2.73	1.20
2	Jiangnan University	30	6.13	167	9.50	5.57
3	Konkuk University	14	2.86	12	0.68	0.86
4	Seoul National University R&DB Foundation	13	2.66	43	2.45	3.31
5	CKD Bio Corporation	11	2.25	28	1.59	2.55
6	Rural Development Administration	10	2.04	8	0.46	0.80
7	Inner Mongolia Yili Industrial Group Co., Ltd.	7	1.43	61	3.47	8.71
8	Korea University Research and Business Foundation	7	1.43	12	0.68	1.71
9	Industry Foundation of Chonnam National University	7	1.43	4	0.23	0.57
10	Chr. Hansen A/S	5	1.02	106	6.03	21.20

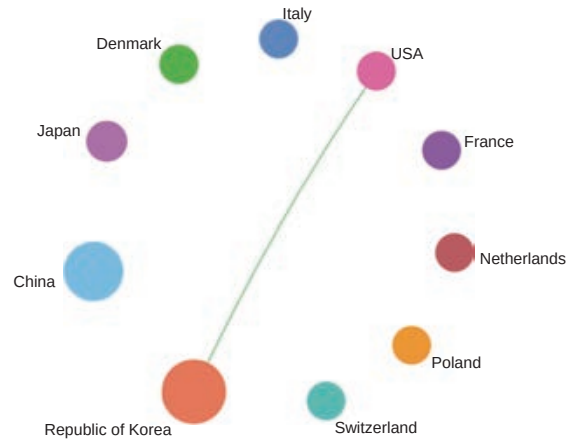


Figure 7.12 Collaboration network among major countries in the engineering development front of "innovative utilization of novel food microbial resources"

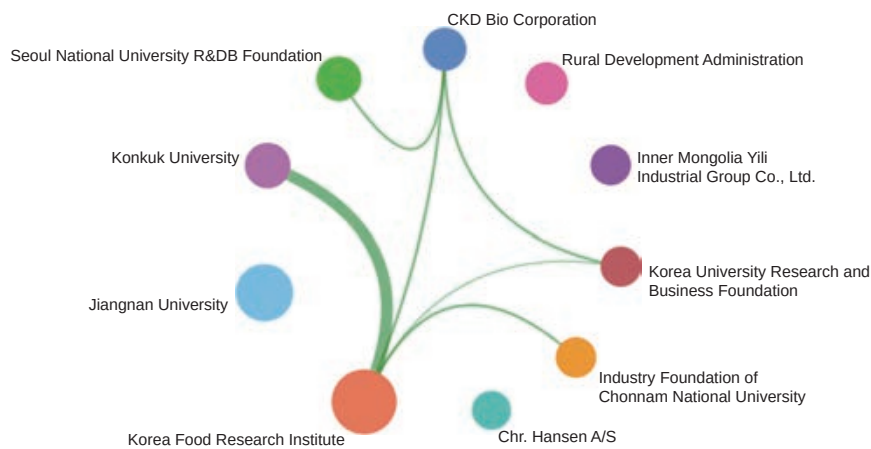


Figure 7.13 Collaboration network among major institutions in the engineering development front of "innovative utilization of novel food microbial resources"

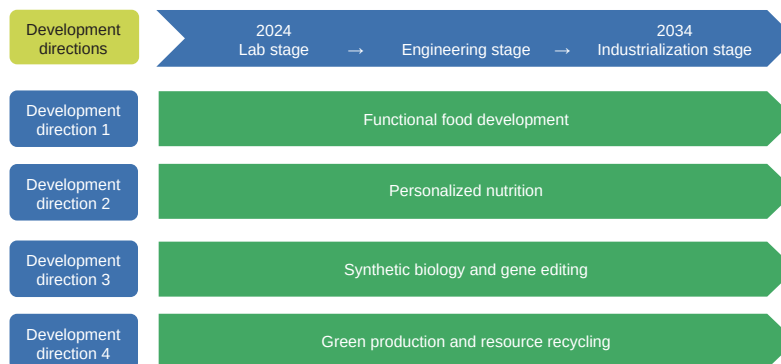


Figure 7.14 Roadmap of the engineering development front of "innovative utilization of novel food microbial resources"

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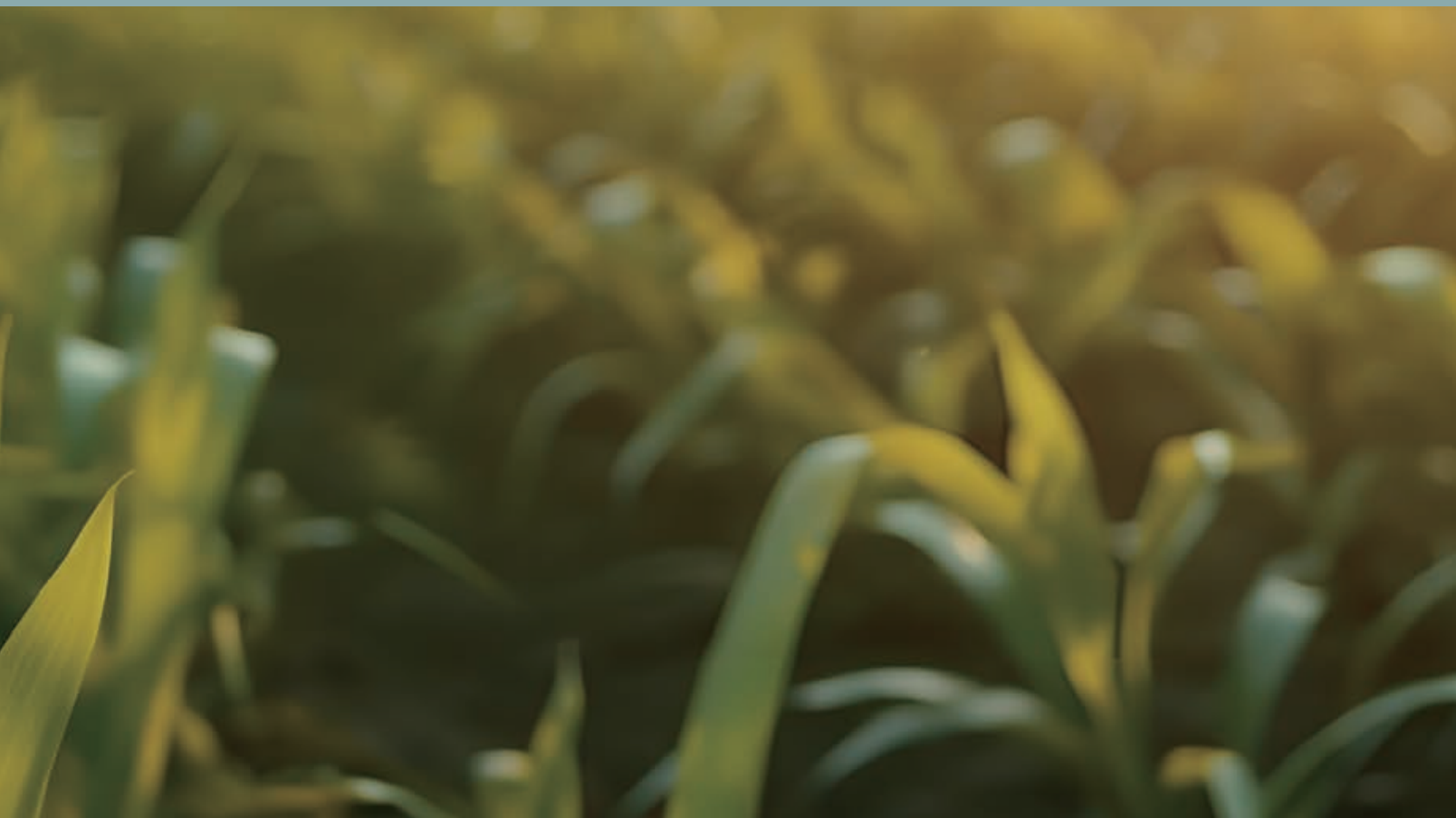
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Chapter 8 Agriculture Fronts



8.1 Engineering research fronts

8.1.1 Trends in the Top 10 engineering research fronts

The top ten engineering research fronts in the field of agriculture reflect the characteristics of agricultural research that focuses more on molecular biology and nutritional health. These fronts include: ① research on the formation mechanism of animal and plant traits and quality, such as “genetic basis for important agronomic traits and environmental adaptation in crops”, “environmental adaptability mechanism of important traits of forest trees”, “the regulatory mechanism for the formation of important traits in livestock and poultry”, and “molecular design of high-quality production for horticultural crops”; ② research on microorganisms and environments that affect human life, such as “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”, “the spectrum and epidemiology of pathogens in wildlife”, “compound hazard effects and control mechanisms of multi-pollutants in agriculture”, and “network mechanism of gut microbiota interaction with feed ingredients in livestock and poultry”; ③ research on emerging technologies and hot topics, such as “research on autonomous agricultural unmanned operation systems” and “discovering of plant key immune receptors and the downstream components”. The number of core papers in the forefront of agricultural engineering research ranges from 14 to 482, with an average of 121 papers, an increase from previous years. The citations per paper ranges from 18.62 to 210.88, with an average of approximately 89.65 articles. The publication years of core papers are mainly in 2019 and 2020. Among them, there are six fronts: “the regulatory mechanism for the formation of important traits in livestock and poultry”, “discovering of plant key immune receptors and the downstream components”, “network mechanism of gut microbiota interaction with feed ingredients in livestock and poultry”, “the spectrum and epidemiology of pathogens in wildlife”, “environmental adaptability mechanism of important traits of forest trees”, and “molecular design of high-quality production for horticultural crops”. The mean year of core papers in three fronts is mainly in 2020: “genetic basis for important agronomic traits and environmental adaptation in crops”, “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”, and “research on autonomous agricultural unmanned operation systems”. Especially for the core paper on the “composite hazard effects and control mechanisms of multiple-pollutants in agriculture”, the average publication year is mainly in 2022, and the number of core papers in 2023 has reached 20, which is closer to the current time compared to other cutting-edge core papers (Tables 8.1 and 8.2).

(1) Genetic basis for important agronomic traits and environmental adaptation in crops

Climate change, agricultural ecological environment deterioration, various abiotic stresses and severe diseases have significantly impacted crops' yield. Even for the same variety, the yield level varies greatly under different growing environments, achieving high and stable yield on the basis of elucidating the genetic network of important agronomic traits is an important goal in crop breeding. Genetic analysis of important trait formation and environmental adaptation in crops refers to in-depth analysis of the genetic basis and regulatory network involved in the formation process of major agronomic traits in crops, and exploration of the genetic mechanisms of crop adaptation under different environmental conditions, in order to realize precise improvement and optimization of major traits such as crop yield, quality and stress resistance. With the rapid development of biotechnology and genomics, research in this area shows the following development trends. Firstly, with the continuous maturity and popularization of large-scale genome sequencing technology, researchers can more deeply analyze genes related to important traits in crop genomes and explore their functions and regulatory mechanisms. Secondly, the application of multi-omics data integration and bioinformatics methods enables more comprehensive analysis of genetic networks involved in the formation of major agronomic traits in crops, revealing interactions and regulatory relationships between different genes. In addition, with increasing demand

Table 8.1 Top 10 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Genetic basis for important agronomic traits and environmental adaptation in crops	482	24 285	50.38	2020.8
2	Mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria	34	633	18.62	2020.7
3	Compound hazard effects and control mechanisms of multi-pollutants in agriculture	35	2 654	75.83	2022.6
4	The regulatory mechanism for the formation of important traits in livestock and poultry	327	14 892	45.54	2019.2
5	Research on autonomous agricultural unmanned operation systems	35	4 165	119.00	2020.0
6	Discovering of plant key immune receptors and the downstream components	76	12 399	163.14	2019.5
7	Network mechanism of gut microbiota interaction with feed ingredients in livestock and poultry	14	1 259	89.93	2019.3
8	The spectrum and epidemiology of pathogens in wildlife	100	21 088	210.88	2019.4
9	Environmental adaptability mechanism of important traits of forest trees	89	4 339	48.75	2019.4
10	Molecular design of high-quality production for horticultural crops	18	1 340	74.44	2019.3

Table 8.2 Annual number of core papers published for the Top 10 engineering research fronts in agriculture

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Genetic basis for important agronomic traits and environmental adaptation in crops	0	0	223	159	79	21
2	Mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria	5	3	8	6	6	6
3	Compound hazard effects and control mechanisms of multi-pollutants in agriculture	0	0	0	0	15	20
4	The regulatory mechanism for the formation of important traits in livestock and poultry	110	98	80	33	6	0
5	Research on autonomous agricultural unmanned operation systems	3	9	14	5	3	1
6	Discovering of plant key immune receptors and the downstream components	27	13	14	14	8	0
7	Network mechanism of gut microbiota interaction with feed ingredients in livestock and poultry	3	5	5	1	0	0
8	The spectrum and epidemiology of pathogens in wildlife	24	28	35	9	4	0
9	Environmental adaptability mechanism of important traits of forest trees	24	25	21	15	4	0
10	Molecular design of high-quality production for horticultural crops	3	3	5	3	1	0

for crop adaptation to different environments, genetic analysis of environmental adaptation is becoming increasingly important in crop genetic improvement. In the future, more emphasis will be placed on the research of genetic mechanisms of crop adaptation

to climate change, soil quality, disease and pest pressure and other abiotic stresses. In summary, genetic analysis of important trait formation and environmental adaptation in crops is an important research area in current crop genetic improvement and varietal selection, driving precise variety improvement and enhancement of adaptability, and making important contributions to achieving food security and sustainable agricultural development.

(2) Mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria

Bacterial resistance, also known as antimicrobial resistance, refers to the ability of bacteria to withstand the effects of antimicrobial drugs, resulting in reduced or even ineffective treatment outcomes. Currently, antimicrobial resistance has become a major global public health issue, particularly due to the widespread use of veterinary antibiotics in animal husbandry, which has made animals a significant source and reservoir of resistant bacteria and resistance genes. The spread of antibiotic-resistant bacteria from animals not only affects animal health and the supply of animal products, but can also be transmitted between humans and animals through the environment and food chains, posing a serious threat to human health and public safety. Therefore, it is crucial to strengthen research on the mechanisms of the emergence, transmission, and control of animal-derived antimicrobial resistance. This includes analyzing the genetic basis of resistance phenotypes, uncovering the structure and function of novel resistance proteins, and elucidating the adaptive changes and regulatory mechanisms of resistant pathogens. Additionally, research should focus on understanding the retention mechanisms of resistance genes and their cross-species and cross-environment transmission, and developing precise risk assessment models for resistance. Furthermore, efforts should be made to discover new targets for combating resistant pathogens, screen for protein lead compounds with potential anti-resistance properties, and promote the development of new antibiotic precursors and precise drug delivery systems. The findings will provide the theoretical foundation for the development of technologies and products to control antimicrobial resistance, contributing to efforts to curb its spread and safeguard both animal and human health.

(3) Compound hazard effects and control mechanisms of multi-pollutants in agriculture

Co-existing pollutants in farmland soil interact synergistically, antagonistically or additively, resulting in more complex hazardous effects on ecosystems and the surrounding environment than those caused by a single pollutant. With the rapid development of agriculture and industry, pollutants such as pesticides, microplastics, antibiotics and heavy metals have been introduced into farmland environment in large quantities. The interactions among these multi-pollutants during physical, chemical and biological processes complicate the environmental impacts of combined pollution, potentially leading to synergistic, antagonistic, or additive effects on soil physicochemical properties, plant and animal growth, and soil microbial communities. Currently, research on multi-pollutants mainly focuses on marine and freshwater environments with the main research directions focusing on ① the effects of multi-pollutants on aquatic plants and animals in the oceans and rivers; ② the study of synergistic or antagonistic effects of multi-pollutants in aquatic environment. However, there is a lack of research on the adsorption-desorption mechanism, co-transportation behavior, driving factors, and green prevention and control technology of combined pollutants in agricultural fields. Further research should aim to clarify the co-transport mechanism of combined pollutants in agricultural fields, develop green prevention and control technologies, and address potential risks to human health, which are critical for the green and sustainable development of agricultural ecosystems.

(4) The regulatory mechanism for the formation of important traits in livestock and poultry

Research on the mechanism of the formation of important shapes of livestock and poultry refers to the study of the genetic basis of economically important traits such as growth and development, meat quality, disease resistance and other important traits of livestock and poultry and their regulatory networks through the integration of genomes, transcriptomes, proteomes and other biological techniques, which is an important prerequisite for the design of breeding of agricultural organisms in our country, and also a strategic guarantee for the scientific and technological innovation of the safety and health of China's livestock and poultry products. China's livestock and poultry breeds are rich in resources, diverse in production types, wide in ecological adaptability, and outstanding in traits, but there are still problems such as insufficient mining of germplasm resources, unclear descriptions of trait characteristics and genetic properties, unclear boundaries of breed identification, low efficiency of phenotypic collection,

and poor accuracy in determination, which results in the existence of a number of bottlenecks in the theory, technology, and standardization of livestock and poultry molecular design and breeding. The rapid development of biological technologies such as high-throughput sequencing has provided a powerful tool for analyzing the formation and regulatory mechanisms of important traits in livestock and poultry, which will help to more accurately screen the variant loci related to important traits. In addition, China's livestock and poultry farming is progressing rapidly with the progress of society and the development of the industry, the contradiction between farming and the environment, animal welfare issues, as well as the large-scale application of automatic recording equipment and various types of sensors in livestock farms have brought a lot of challenges to China's livestock and poultry farming, and the emergence of the mechanism of the new traits is also the inevitable momentum of the industry's development, which is important for the adaptation to the current trend of environmental change under the sustainable development of agriculture. It is of great significance to adapt to the sustainable development of agriculture under the current trend of environmental change.

(5) Research on autonomous agricultural unmanned operation systems

Autonomous agricultural unmanned operation system refers to the unmanned agricultural production and operation technology and system integration that can actively sense information and make scientific decisions, and realize all-weather, all-process, all-space unmanned agricultural production and operation technology by autonomous unmanned operation equipment such as intelligent agricultural machines and agricultural robots. This system is the implementation of smart agriculture and an effective way to solve the problem of "who will farm and how to farm". Aiming at the unstructured and complex farm environment, the autonomous agricultural autonomous unmanned operation system focuses on breaking through the following key theories and technologies: ① the accurate sensing mechanism and sensing technology of the autonomous unmanned operation equipment, operation environment and operation objects; ② the scene cognition method based on multi-source perception of heterogeneous information, and the autonomous decision-making, planning and control technology based on job flow and machine learning in the all-terrain, multi-obstructed and dynamic agricultural scenarios; ③ design and accurate and efficient operation technology of operating device, terminal actuator and manipulator integrated with advanced agronomics; ④ key technologies of autonomous unmanned operation equipment group realize real-time communication, group autonomous collaboration and human-machine integration; ⑤ the settlement of the whole process of the integration of autonomous unmanned operation equipment to realize the unmanned production and operation mode of all-weather, all-process, all-space production of farms. Autonomous agricultural unmanned operation system is the most advanced agricultural new quality productivity, which can completely liberate agricultural labor, greatly improve productivity, resource utilization and output rate, and realize agricultural intelligent production.

(6) Discovering of plant key immune receptors and the downstream components

Immune receptors play essential roles in disease resistance in plants. There are two types of immune receptors, the plasma membrane located PRR receptors and the cytosol NBL receptors. Typical PRR receptors contain an extracellular domain, a transmembrane domain and a cytosolic kinase domain. The extracellular domains perceive conserved molecular features of pathogens, which results in the intracellular domain phosphorylation, the activation. While, the cytosol NBL receptors contain a CC or TIR domain, a NBS domain and a LRR domain. They perceive pathogen-secreted effectors, which typically causes hypersensitive response (cell death) to prevent pathogen proliferation. Due to the known domains, these receptors can be easily identified by genome sequencing and bioinformatic analysis. However, to prove that they are immune receptors, the gene function analysis through biochemical approaches is necessary, especially for the questions that how they are activated, their ligands, and the downstream components.

It is a longstanding mystery how these receptors are activated. The breakthrough work by Jijie Chai, Tsinghua University and Jianming Zhou, the Institute of Genetics and Developmental Biology, Chinese Academy of Sciences has lighted up the immunity field, where they resolved the crystal structure of immune receptor "resistome" and answered how the immune receptor was activated and how the signal was transduced to downstream components. Since then, many key immune receptor complex structures were resolved, where the complex conformation changes and the immune activation mechanisms were well addressed. These achievements also greatly help elucidate the roles of the downstream components, including the helper NBLs. Based on the understanding of the immune complex activation, scientists can play the pieces and create novel disease resistant plants now.

In addition to these achievements, the PRR discovery and activation are also attractive to the whole community, where the new downstream components, signal transduction and the distinguishing of beneficial microorganisms remain largely unknown.

(7) Network mechanism of gut microbiota interaction with feed ingredients in livestock and poultry

The gut microbiome refers to the community of microorganisms residing in the intestines of livestock and poultry. These microorganisms engage in complex interactions with the host and nutrients in the feed, influencing the growth, health, and feed conversion efficiency of livestock. The interaction between the gut microbiome and feed nutrition is primarily achieved through several mechanisms. Firstly, the gut microbiome can break down complex feed components, such as cellulose, lignin, and other non-starch polysaccharides. These components are fermented and metabolized by the gut microorganisms, producing metabolites that not only provide energy to the host but also regulate the gut environment, promoting intestinal health. Secondly, the gut microbiome can synthesize essential nutrients that the host cannot produce on its own, such as vitamin K and certain amino acids, which are crucial for the growth and development of livestock. Additionally, feed composition can significantly impact the composition and function of the gut microbiome. For example, high-fiber feed intake can promote the proliferation of fiber-degrading bacteria, while high-protein feed intake may increase the abundance of gas-producing and ammonia-producing bacteria, thereby affecting the gut environment and the digestive and absorptive efficiency of the animals. The connection between the gut microbiome and feed nutrition is a complex, multi-level regulatory system that involves not only microbial metabolic pathways and gene expression regulation but also interactions between microorganisms and the host. The application of single-omics or multi-omics technologies holds promise for further elucidating these complex network mechanisms, and these findings can help optimize feed formulations, improve nutrient absorption, and enhance farming efficiency and animal health.

(8) Pathogen spectrum and epidemiological research in wildlife

With the rapid growth of the global population, the vast expansion of human activities, environmental degradation, and frequent contact between humans and wildlife, pathogens such as virus, bacteria, fungi, and parasites are increasingly cross species barriers. This has led to the continuous emergence and re-emergence of zoonotic diseases worldwide. Wildlife serves as a reservoir and source for many emerging and re-emerging zoonotic pathogens, with over 70% of newly emerging infectious diseases in humans originating from wildlife or related vectors. The pathogens carried by wildlife have become a major challenge to public health in the future. These zoonotic pathogens are carried by a wide range of wildlife, including mammals, birds, and insects. Due to the diversity of pathogens carried by wildlife and the complexity of their transmission routes and circulatory systems, conventional pathogen detection methods often fail to accurately identify novel pathogens. Therefore, it is crucial to systematically conduct a nationwide survey of wildlife pathogen spectra using macrogenomics analysis. This will lay the foundation for researching important novel pathogens, establishing a genetic database, assessing the risk of cross-species transmission to humans, and providing original strains for subsequent research. This approach will also enable rapid tracing and source analysis in the event of future outbreaks, thereby playing a significant role in the surveillance, early warning, and early diagnosis of emerging zoonotic pathogens.

(9) Environmental adaptability mechanism of important traits of forest trees

Forest trees provide renewable resources and play an extremely important role in maintaining the stability and health of the Earth's ecosystem, forests with high quality and diverse functions are thereby particularly important for human survival and sustainable development. However, the perennial nature of forest trees makes them vulnerable to the impact of climate and environmental changes, resulting in changes in important traits such as quality, function, and yield. How these changes are generated and how they can meet the target needs of humans has become a major scientific topic of international concern. The systematic study of the environmental adaptability mechanism of important traits such as quality and function in forest trees is the key foundation for answering this proposition. Therefore, several aspects of frontier research in forest trees need to be carried out, including: ① analyzing the changes in forest quality and function traits in response to environmental factors such as temperature, light, water, and carbon dioxide levels, as well as the molecular genetic pathways underlying the directional differentiation of stem cells in trees in response to climate and environmental changes; ② exploring key factors including specific molecular module elements and regulatory networks that coordinately control multiple traits such as forest growth, quality formation, environmental adaptability, and function; ③ elucidating the biological mechanisms of synergistic regulation of important traits such as growth

and development, quality, stress resistance, as well as the adaptation to changing environments in forest trees. Based on these, biological breeding strategies can be further proposed for targeted regulation of important traits such as forest quality and function under the conditions of changing climate and environment, which is the source drive of bottleneck breakthrough in breeding technology for excellent tree varieties under the background of global climate change. These outputs will provide the scientific basis for formulating strategies of forest tree seed industry to address climate and environmental change in China, and to serve the implementation of major national strategies such as carbon neutrality.

(10) Molecular design of high-quality production for horticultural crops

As people's demands for horticultural crop quality increase, including better taste, higher nutritional value, and improved appearance, these have become new breeding goals. Molecular design breeding, which combines modern biotechnology with traditional methods, is a key approach to cultivating high-quality horticultural crops. The core idea of molecular design breeding is based on a deep understanding of crop genomes and functional genomics, using techniques like gene editing and molecular marker-assisted selection to precisely regulate quality-related genes, optimizing appearance, nutritional content, and flavor traits. Currently, molecular design breeding faces challenges in horticultural crops, such as the complexity of polyploid and heterozygous genomes, difficulties in evaluating quality traits, and limitations in technical platforms. Technologically, using tools like mass spectrometry and hyperspectral imaging to accurately and efficiently assess quality traits helps clarify their causes and influencing factors, providing the genomic foundation for molecular design. Whole-genome selection strategies, especially pangenomics, are important directions for studying the domestication, formation, and application of complex quality traits. By collecting, evaluating, and mining crop resources, identifying all genetic diversity within species, and discovering new quality-related genes, combined with new gene editing tools like CRISPR-Cas9, breeders can access more comprehensive genetic resources. Integrating multi-omics data (genomics, transcriptomics, metabolomics, and phenomics) to build multi-level regulatory networks for quality traits enables the precise identification of key genes and metabolic pathways. On this basis, artificial intelligence and machine learning, using algorithms like deep learning and random forests, can predict complex relationships between genotypes and quality traits, further enhancing molecular design breeding at a higher level.

8.1.2 Interpretations for three key engineering research fronts

8.1.2.1 Mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria

(1) Research significance

Bacterial resistance, also known as antimicrobial resistance, refers to the ability of bacteria to withstand the effects of antimicrobial drugs, rendering these drugs less effective or even ineffective. Resistant bacteria can disrupt the balance between the microbiome, host, and environment, leading to the transformation of normal flora into opportunistic pathogens, compromising the immune system, inducing diseases, and increasing treatment failure and mortality rates. Currently, antimicrobial resistance has become a major global public health issue. In the livestock industry, the frequent use of antimicrobial drugs, particularly as growth promoters in feed, has led to the widespread emergence and dissemination of resistant bacteria and genes. Livestock farms have become major sources of resistant bacteria and genes, and animals have become important reservoirs for these resistant strains. The extensive spread of animal-derived resistant bacteria and genes not only complicates animal disease control but can also spread through the environment and food chain to humans, posing significant threats to human health and the ecosystem. The complexity, hidden nature, and long-term persistence of bacterial resistance present challenges, such as unclear mechanisms of formation, unknown transmission patterns, weak monitoring systems, insufficient risk assessment, and outdated control technologies. Therefore, it is imperative to enhance research on the mechanisms of emergence, transmission, and control of animal-derived antimicrobial resistance, which is crucial for curbing the spread of antimicrobial resistance, ensuring sustainable livestock development, maintaining food safety, protecting the environment, and safeguarding global public health.

(2) Current research status

Antimicrobial resistance is characterized by rapid development, expanding resistance spectrum, increasing resistance intensity, and

accelerated transmission. The livestock industry is considered one of the primary sources of resistant bacteria and genes, with an estimated 60% of human pathogens originating from animal-derived pathogens. The horizontal transfer of resistance genes is a key reason for the widespread dissemination of these resistant bacteria. Resistance genes are often located on mobile genetic elements, such as plasmids, transposons, or integrons, which allow horizontal transfer between bacteria through conjugation, transformation, or transduction. For example, genes encoding extended-spectrum β -lactamases (ESBLs), which can hydrolyze most penicillins and cephalosporins, have been identified in over 600 variants, many of which are located on mobile plasmids and can rapidly spread between different bacteria through conjugation, especially CTX-M strains that are prevalent in the livestock industry. Although carbapenems are not approved for use in animal farming, carbapenemase-producing bacteria (e.g., NDM) have spread in livestock environments and animal-derived foods, highlighting the selection pressure imposed by antimicrobial drug use. Colistin, a last-resort drug for treating multidrug-resistant infections in humans, has been widely used in the livestock industry, leading to the emergence and spread of transferable colistin resistance genes, such as *mcr-1*. Since its discovery in 2016, *mcr-1* has spread in over 60 countries among both animals and humans. Tigecycline, a third-generation tetracycline drug, has been reported in animals to carry plasmid-mediated resistance genes *tet(X3)/tet(X4)* and *tmexCD1-toprJ1* in 2019 and 2020 in China. The widespread use of florfenicol in animal farming has led to the discovery of multiple resistance genes, such as *cfr* and *optrA*, which also mediate resistance to linezolid, the last-resort drug for Gram-positive infections in human medicine. The widespread prevalence of these resistant bacteria and genes in livestock and their environments is driven by multiple factors, including differences in farming practices, antimicrobial drug residues, heavy metal pollution, disinfectant use, and environmental vectors. Long-term, extensive use of antimicrobial drugs in livestock farming results in residues in the environment, promoting the selection and accumulation of resistant bacteria and genes, which are the primary drivers of resistance emergence and dissemination. High-density farming and animal movement increase the frequency of resistant bacteria exchange, accelerating the spread of resistance. Antimicrobial drugs in animal waste also exert selective pressure on environmental microorganisms, further expanding resistance in the environment. Heavy metals, such as copper and zinc, commonly used in animal feed, also provide selective pressure for resistant bacteria, facilitating the co-selection and dissemination of resistance. Additionally, vectors such as rodents, birds, and flies play a role in the mechanical transmission of resistant genes. Studies have shown that resistant genes can spread through slaughter, processing, and logistics into markets and community environments, further exacerbating dissemination. Control mechanism research is key to halting the development of resistance, including new drug screening and antimicrobial target mechanism studies. Developing new antimicrobial drugs remains the most effective means of controlling the emergence and spread of bacterial resistance. Of 407 preclinical antimicrobial projects globally, more than 70% focus on small-molecule compounds, with small and medium-sized enterprises and academic institutions leading the efforts. However, in the past 15 years, no new antimicrobial drugs targeting novel mechanisms have been approved for clinical use. The 13 small-molecule antimicrobials approved by the FDA are all from existing drug classes with high cross-resistance rates. Additionally, the development of alternative therapies to current antimicrobials shows promise for controlling resistance spread. Targeted gene-editing technologies, such as CRISPR-Cas9, have been applied to remove resistance genes from bacteria, offering new possibilities for inhibiting the spread of resistance genes. Furthermore, alternative antimicrobial research has progressed, with Chinese veterinary medicine (plant extracts), probiotics (microecological agents), antimicrobial peptides, bacteriophages, vaccines, and enzymes gaining widespread attention and becoming hotspots in resistance control research.

(3) Future research directions and innovations

Antimicrobial resistance spans the entire “animal-environment/food-human” chain. Therefore, based on the “One Health” strategy, promoting cross-sectoral, interdepartmental, and interdisciplinary research cooperation, will be key to curbing resistance spread. In terms of resistance emergence, research should focus on key animal pathogens, analyze the genetic basis of major resistance phenotypes, elucidate the structure and function of novel resistance proteins, reveal the link between pathogen resistance and virulence, and determine the retention mechanisms of resistant pathogens and genes. For resistance transmission, systematic and continuous surveys are needed to obtain baseline and dynamic data on animal-derived bacterial resistance, analyze the mechanisms of resistance gene emergence and their transmission across hosts and environments, and identify the driving factors. The development of intervention measures and risk assessment models for resistant pathogens will also be crucial. In terms of resistance control, research should focus on discovering, designing, and modifying new veterinary drug molecules based on novel targets, elucidating the interaction mechanisms between targets and small molecules, identifying new targets for resistant pathogens, and screening natural or synthetic ligands for these targets.

Furthermore, the discovery of lead compounds that inhibit resistance protein functions and enhance antimicrobial efficacy, along with the development of novel antibiotic precursors, will provide theoretical support for the creation of new antimicrobials. Additionally, the development of new veterinary antibiotic alternatives, resistance-reducing agents, and the study of combination therapies for resistant pathogens, as well as the exploration of drug synergy and reduced toxicity mechanisms, will offer solutions for controlling bacterial resistance. Establishing new drug delivery systems, such as microencapsulation and nanotechnology, and developing new compound formulations for oral and inhalation use will further contribute to resistance control efforts.

In the front of “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”, the top three countries in terms of the publication of core papers (Table 8.3) are China (25.53%), the USA (20.59%), and Germany (8.82%). The citation per paper in this research field ranges from 5.00 to 69.00. In terms of research institution contributions (Table 8.4), the Free University of Berlin (FU Berlin) and Bangladesh Agricultural University (BAU) have produced many core papers and have been cited frequently. Regarding international cooperation (Figure 8.1), research cooperation among countries is more common, with particularly close cooperation between China and Egypt. The primary output is found within the cooperation network among institutions (Figure 8.2), where certain collaborative relationship is relatively few. The main countries contributing to citing papers are China, the USA, and Germany, with China accounting for more than 1/4 and the USA accounting for 23.95% (Table 8.5). In terms

Table 8.3 Countries with the greatest output of core papers on “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	8	23.53	141	17.62	2020.1
2	USA	7	20.59	256	36.57	2020.4
3	Germany	3	8.82	207	69.00	2019.7
4	Egypt	3	8.82	60	20.00	2020.3
5	Japan	3	8.82	58	19.33	2019.7
6	Saudi Arabia	3	8.82	17	5.67	2022.0
7	Brazil	2	5.88	36	18.00	2021.0
8	Bangladesh	2	5.88	35	17.50	2020.5
9	UK	2	5.88	21	10.50	2021.5
10	Spain	2	5.88	10	5.00	2022.5

Table 8.4 Institutions with the greatest output of core papers on “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Free University of Berlin	2	5.88	207	103.50	2018.0
2	Bangladesh Agricultural University	2	5.88	35	17.50	2020.5
3	Zagazig University	2	5.88	31	15.50	2020.5
4	United States Department of Agriculture-Agricultural Research Service	2	5.88	16	8.00	2021.5
5	Centre de Recerca en Sanitat Animal	2	5.88	10	5.00	2022.5
6	Kansas State University	1	2.94	176	176.00	2018.0
7	Zoetis Global Therapeutics Research	1	2.94	176	176.00	2018.0
8	Charles University in Prague	1	2.94	51	51.00	2018.0
9	Chiba University	1	2.94	51	51.00	2018.0
10	Chinese Academy of Sciences Institute of Microbiology	1	2.94	51	51.00	2018.0

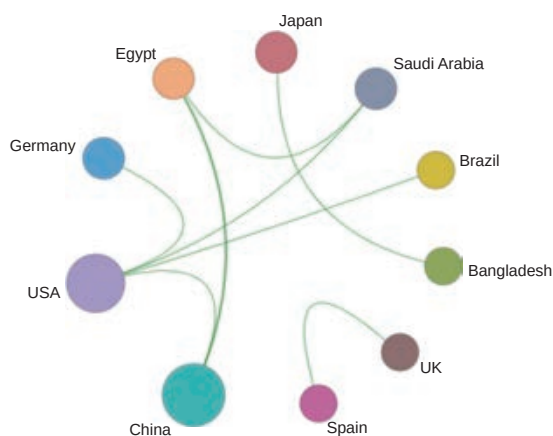


Figure 8.1 Cooperation network among major countries in the engineering research front of “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

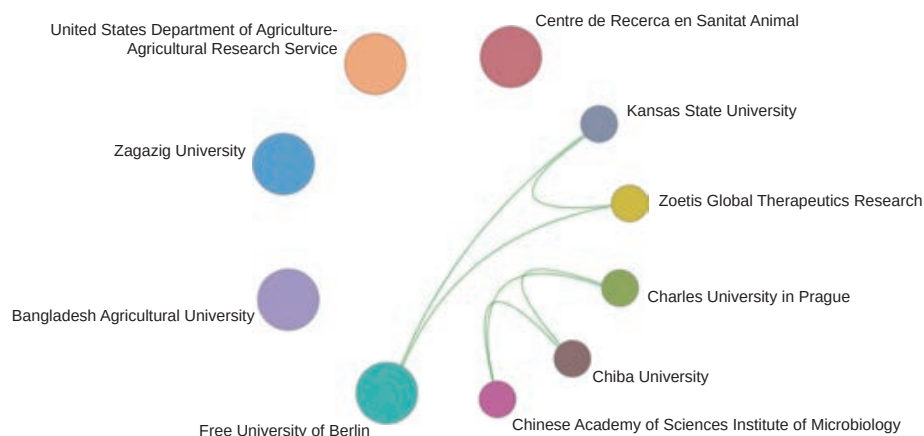


Figure 8.2 Cooperation network among major institutions in the engineering research front of “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

Table 8.5 Countries with the greatest output of citing papers on “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	136	26.05	2021.9
2	USA	125	23.95	2021.7
3	Germany	45	8.62	2021.6
4	Egypt	40	7.66	2022.1
5	Brazil	37	7.09	2021.6
6	Bangladesh	32	6.13	2021.9
7	Saudi Arabia	22	4.21	2022.5
8	UK	22	4.21	2021.3
9	Australia	21	4.02	2021.6
10	Italy	21	4.02	2022.2

of the main output institutions of the citing papers (Table 8.6), the Bangladesh Agricultural University (BAU), the Free University of Berlin (FU Berlin), and the Charles University (CU) ranked among the top three in the number of citing papers. Figure 8.3 shows the roadmap of the engineering research front of “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”.

Table 8.6 Institutions with the greatest output of citing papers on “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

No.	Institutions	Citing papers	Percentage of citing papers/%	Mean year
1	Bangladesh Agricultural University	22	15.38	2021.7
2	Free University of Berlin	19	13.29	2021.4
3	Charles University in Prague	14	9.79	2021.1
4	Zhejiang University	14	9.79	2022.2
5	University of Veterinary Medicine	12	8.39	2020.2
6	Tanta University	12	8.39	2022.4
7	Westerdijk Fungal Biodiversity Institute	11	7.69	2021.2
8	University of Malaya	10	6.99	2022.3
9	University of Sao Paulo	10	6.99	2020.7
10	Czech Republic Academy of Sciences	10	6.99	2021.1

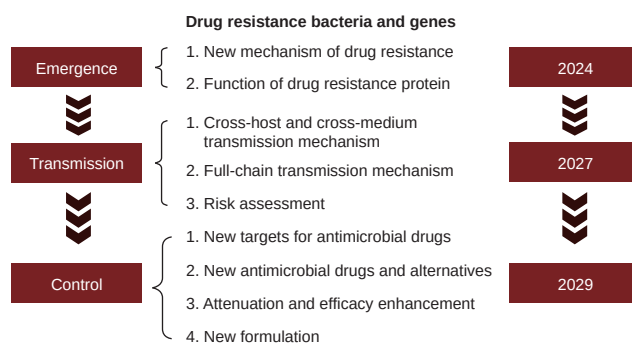


Figure 8.3 Roadmap of the engineering research front of “mechanisms of emergence, transmission, and control of antimicrobial resistance in animal-derived bacteria”

8.1.2.2 Compound hazard effects and control mechanisms of multi-pollutants in agriculture

(1) Research significance

The presence of multi-pollutants in agricultural soil leads to complex interactions, where pollutants co-existing in farmland soils interact synergistically, antagonistically or additively. These interactions produce more harmful effects on the ecosystem and the surrounding environment than those caused by a single pollutant. With the rapid development of industry and agriculture, pollutants such as pesticides, microplastics, antibiotics and heavy metals have entered the farmland environment in large quantities.

Microplastics, as a new type of environmental persistent pollutants, possess a high adsorption capacity, allowing them to act as

carriers for other pollutants. This capability can exacerbate or mitigate the toxicity of organic pollutants on biological systems, thereby creating compounded hazardous effects on the environmental media. Heavy metals and pesticides, which are prevalent environmental contaminants, accumulate easily and degrade slowly in soil environments. These pollutants often exhibit synergistic or antagonistic effects. Heavy metal pollution, in particular, not only affects the respiration of soil microorganisms, enzyme activity, microbial population and community structure, but also affects plant growth indirectly or directly by altering soil structure or affecting the enzyme activity in the rhizosphere. In addition, antibiotics molecules, containing numerous carboxyl and hydroxyl groups, can complex with metal ions, thereby changing the environmental behavior and toxicological effects of the pollutants within the composite pollution. In summary, the interaction among agricultural multi-pollutants during physical, chemical and biological processes result in complex environmental effects. These interactions can have synergistic, antagonistic, or even additive effects, significantly influencing the physicochemical properties of soil, plant and animal growth, and soil microbial communities.

The research on the compound hazard effects of agricultural multi-pollutants and green prevention and control mechanism is of great significance for promoting the sustainable agricultural development. Such research not only contributes to protection and improvement of the agro-ecological environment and ensures the quality and safety of agricultural products, but also plays a crucial role in enhancing the stability and productivity of the agro-ecosystem. Therefore, it is important to study the combined hazard effects of multi-pollutants in agriculture and conduct rational green control mechanisms to assess agro-ecological safety and soil health.

(2) Current research status

Microplastics, pesticides, antibiotics, and heavy metals are widely present in agricultural soils, and the potential for these pollutants to compound and influence each other in the aquatic environment has now been demonstrated. Microplastics were found to enhance the bioaccumulation of rotenone in fish tissues compared to exposure to rotenone alone. Combined exposure to polystyrene microplastics and antibiotics had a significant inhibitory effect on the growth and parameters of *P. obliquus*, and in the case of *Daphnia magna*, the combined exposure had an additive effect on its superoxide dismutase activity. In agricultural soils, due to the resource utilization of organic fertilizers from livestock and poultry manure, antibiotics, heavy metals and microplastics coexist in the soil, resulting in a complex pollution effect that is more complicated than that in marine and freshwater environments, but there is a lack of research on complex pollutants in agricultural soils, and it is worthwhile to further investigate the hazardous effects of complex pollution. Existing studies found that when microplastics, antibiotics and heavy metals coexisted in soil, microplastics reduced the degradation rate of antibiotics and increased the abundance of resistance genes, and heavy metals increased the negative impact of microplastics on soil animals, but the composite pollution did not deepen the accumulation of antibiotics itself, and even reduced the bioavailability of some heavy metals by changing their morphology. Therefore, it is controversial whether microplastics and antibiotics heavy metals have toxic synergistic effects, and its mechanism of action needs to be further studied in depth. Therefore, the current research deficiencies are mainly as follows: ① The adsorption-desorption behaviors of microplastics on typical pollutants of agricultural soils such as heavy metals, pesticides and antibiotics need to be further revealed. ② Microplastics can migrate horizontally and vertically in agricultural soils, but the co-transport behaviors and driving factors of microplastics and typical pollutants in agricultural soils, such as heavy metals, pesticides and antibiotics, are not yet clear. ③ At present, there is a lack of research on green prevention and control technology for the compound pollution of microplastics with heavy metals, pesticides and antibiotics.

(3) Future research directions and innovations

Research on the hazardous effects of agricultural multi-pollutant composites and green prevention and control mechanisms need to be further advanced in the following fields. ① Focus on the co-transport of typical pollutants in agricultural soils, such as microplastics, heavy metals, pesticides and antibiotics. Further clarification of the interaction mechanism of combined pollutants in the soil environment and their environmental behavior in the soil ecosystem is needed, particularly in terms of interfacial processes. Strengthening research on the adsorption-desorption behavior of various pollutants in farmland and exploring the intrinsic mechanisms and influencing factors are also essential. ② Consider the comprehensive impact of combined pollutants on soil ecosystems in agricultural fields and their green prevention and control technologies. It is crucial to account for the natural soil and the elements in the soil ecosystem to assess the toxic effects of combined pollution. Developing combined pollution

prevention and control techniques will provide technical support for future soil prevention and remediation. ③ Examine the environmental exposure pathway of combined pollution in farmland and its potential risk to human health. By revealing the exposure process of combined pollution, the human health risk associated with it can be better understood.

In the front of “compound hazard effects and control mechanisms of multi-pollutants in agriculture”, the top three countries in terms of the publication of core papers (Table 8.7) are the USA (31.43%), China (31.43%), and Australia (20.00%). The citations per paper in this research field ranges from 41.73 to 118.25, with Italy’s citations per paper exceeding 100. In terms of research institution contributions (Table 8.8), the Cairo University, Fayuom University, and University of Delhi have produced many core papers and have been cited frequently. Regarding international cooperation (Figure 8.4), research cooperation among countries is more common, with particularly close cooperation between China and Australia. The primary output is found within the cooperation network among institutions (Figure 8.5), where certain collaborative relationship exist. The main countries contributing to citing papers are China, India, and the USA, with China accounting for more than 1/3 and India accounting for more than 12% (Table 8.9). In terms of the main output institutions of the citing papers (Table 8.10), the Chinese Academy of Sciences, the King Saud University, and the China Agricultural University ranked among the top three in the number of citing papers. Figure 8.6 shows the roadmap of the engineering research front of “compound hazard effects and control mechanisms of multi-pollutants in agriculture”.

Table 8.7 Countries with the greatest output of core papers on “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	11	31.43	764	69.45	2022.5
2	China	11	31.43	459	41.73	2022.6
3	Australia	7	20.00	536	76.57	2022.4
4	India	6	17.14	551	91.83	2022.3
5	Spain	6	17.14	421	70.17	2022.7
6	Egypt	6	17.14	277	46.17	2022.3
7	Pakistan	5	14.29	297	59.40	2022.8
8	Italy	4	11.43	473	118.25	2022.2
9	UK	4	11.43	313	78.25	2022.5
10	United Arab Emirates	3	8.57	239	79.67	2022.3

Table 8.8 Institutions with the greatest output of core papers on “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Cairo University	3	8.57	159	53.00	2022.0
2	Fayuom University	3	8.57	118	39.33	2022.3
3	University of Delhi	2	5.71	214	107.00	2022.5
4	University Western Australia	2	5.71	120	60.00	2022.5
5	The University of Georgia	2	5.71	106	53.00	2022.0
6	China Agricultural University	2	5.71	102	51.00	2022.5
7	Murdoch University	2	5.71	96	48.00	2022.0
8	Nanjing Normal University	2	5.71	96	48.00	2022.0
9	Umm Al-Qura University	2	5.71	96	48.00	2022.0
10	United Arab Emirates University	2	5.71	96	48.00	2022.0



Figure 8.4 Cooperation network among major countries in the engineering research front of “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

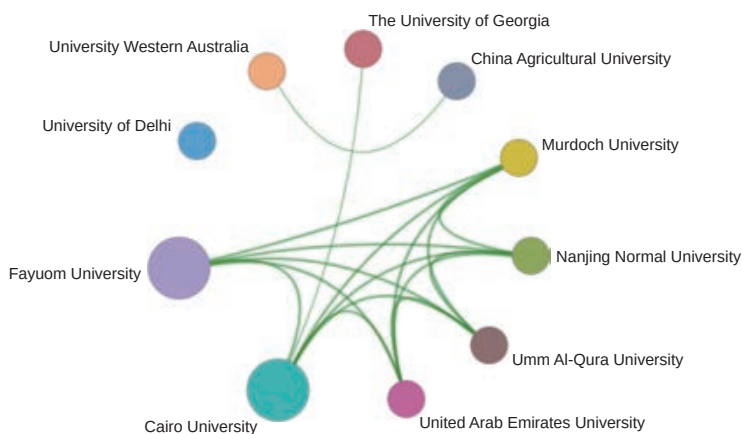


Figure 8.5 Cooperation network among major institutions in the engineering research front of “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

Table 8.9 Countries with the greatest output of citing papers on “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	889	38.82	2023.0
2	India	280	12.23	2023.0
3	USA	270	11.79	2022.9
4	Saudi Arabia	141	6.16	2023.0
5	Italy	121	5.28	2023.0
6	UK	112	4.89	2022.9
7	Republic of Korea	107	4.67	2023.0
8	Australia	100	4.37	2022.9
9	Spain	94	4.10	2023.0
10	Brazil	88	3.84	2023.0

Table 8.10 Institutions with the greatest output of citing papers on “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

No.	Institutions	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	120	30.30	2022.9
2	King Saud University	50	12.63	2023.0
3	China Agricultural University	40	10.10	2023.0
4	Zhejiang University	35	8.84	2022.9
5	Chinese Academy of Agricultural Sciences	28	7.07	2023.0
6	University of Florida	23	5.81	2023.0
7	Northwest Agriculture and Forest University	22	5.56	2023.0
8	King Khalid University	21	5.30	2023.0
9	Shanghai Jiao Tong University	20	5.05	2022.9
10	Aarhus University	19	4.80	2022.9

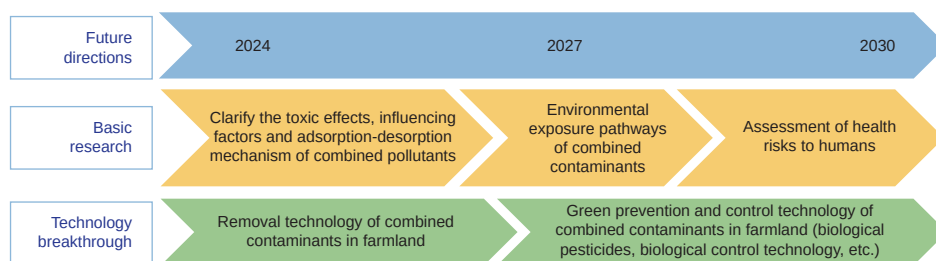


Figure 8.6 Roadmap of the engineering research front of “compound hazard effects and control mechanisms of multi-pollutants in agriculture”

8.1.2.3 The regulatory mechanism for the formation of important traits in livestock and poultry

(1) Research significance

Research on the mechanism of the formation of important shapes of livestock and poultry refers to the study of the genetic basis of economically important traits such as growth and development, meat quality, disease resistance and other important traits of livestock and poultry and their regulatory networks through the integration of genomes, transcriptomes, proteomes and other biological techniques, which is an important prerequisite for the design of breeding of agricultural organisms in our country, and also a strategic guarantee for the scientific and technological innovation of the safety and health of China's livestock and poultry products. China's livestock and poultry breeds are rich in resources, diverse in production types, wide in ecological adaptability, and outstanding in traits, but there are still problems such as insufficient mining of germplasm resources, unclear descriptions of trait characteristics and genetic properties, unclear boundaries of breed identification, low efficiency of phenotypic collection, and poor accuracy in determination, which results in the existence of a number of bottlenecks in the theory, technology, and standardization of livestock and poultry molecular design and breeding. The rapid development of biological technologies such as high-throughput sequencing has provided a powerful tool for analyzing the formation and regulatory mechanisms of important traits in livestock and poultry, which will help to more accurately screen the variant loci related to important traits. In addition, China's livestock and poultry farming is progressing rapidly with the progress of society and the development of the industry, the contradiction between farming and the environment, animal welfare issues, as well as the large-scale application of automatic recording equipment and various types of sensors in livestock farms have brought a lot of challenges to China's

livestock and poultry farming, and the emergence of the mechanism of the new traits is also the inevitable momentum of the industry's development, which is important for the adaptation to the current trend of environmental change under the sustainable development of agriculture. It is of great significance to adapt to the sustainable development of agriculture under the current trend of environmental change.

(2) Current research status

The current research on the regulatory mechanisms of important traits in livestock and poultry mainly focuses on the annotation of the structure and function of livestock and poultry genes, as well as the impact of genes, genetic variation on phenotypes and phenotypic variation and their mechanisms. In the past 30 years, a great deal of research has been carried out at home and abroad on the molecular mechanisms surrounding the formation of traits such as yield, quality, reproduction and health in pigs, cattle, sheep and various types of poultry. Through genome-wide association analysis, a large number of molecular markers associated with various traits and diseases of livestock and poultry have been found, many candidate genes have been screened, and some important quantitative trait loci have been identified. For example, domestic researchers carried out genome-wide association analysis of Duroc pigs, revealing the difference between Duroc pigs and other breeds in growth and meat quality traits; a large number of Chinese Holstein cows in the Beijing area for the test, the results show that the *RPL23A* and *ACACB* gene loci can be directly or indirectly through the pathway to affect the milk fat or milk protein traits of the cows, the milk production traits play an important role in the regulation of milk; Genome-wide association analysis of reproductive traits in three breeds of Polish sheep by foreign scientists revealed the importance of the *EPHA6* gene for high sheep production.

Many of the significant candidate genes and mutation sites identified by genome-wide association analysis do not determine whether they affect protein formation, making it difficult to conduct precise causal variation studies. Therefore, further in-depth mining of the analyzed DNA markers and quantitative trait loci is required to identify trait-determining quantitative trait loci and thus elucidate the underlying causes of trait variation. Compared with prediction models based solely on genomic variation data, multi-omics data can complement subtle phenotype-related features that are difficult to capture at the genomic level and improve the accuracy of genomic prediction of complex traits. Currently, international attempts are being made to incorporate other multi-omics data within genome-wide selection models, and to utilize integrated multi-omics to analyze the regulatory mechanisms of important trait formation in livestock and poultry. Jiang Yu team of Northwest Agriculture and Forestry University constructed the pan-genome of cattle, sheep, pigs, chickens and ducks, and based on the pan-genome for a number of important economic traits gene mining; domestic and foreign research teams have successively located a number of livestock and poultry growth and development, reproduction, coat color, disease resistance and other important traits formation and evolution of genes related to some of the functional genes play a common role in different agricultural animals. Meanwhile, artificial intelligence represented by deep learning has become an efficient tool for mining multi-omics data. Deep learning-based multi-omics data integration algorithms have achieved excellent prediction performance in some fields, such as the construction of disease regulatory networks, and the use of artificial intelligence models to accurately predict the relevant genetic loci, providing target sites for the precise design of livestock and poultry molecular breeding.

Complex traits are first controlled by heredity or genes, and this genetic variation is also considered to be the first level of control. However, organisms with consistent genetic information can also exhibit different traits depending on chromatin modifications, and this epigenetic variation is considered to be the second level of control; the same organism with consistent genetic and epigenetic modifications can still exhibit different traits in different environments, and this environmental variation resulting from the interaction of the organism with the environmental variation resulting from organism-environment interactions is considered to be the third level of control. The synergistic interactions among the three levels of genetic variation, epigenetic variation and environmental variation precisely control the formation of complex traits and determine the different phenotypes of species. In addition, in trait determination, there are certain associations and interactions among different traits. The underlying principle is the interaction and coupling between multi-dimensional controls in each trait decision, for example, while mutating *DGAT1* and *GHR* loci to increase milk production in dairy cows, the percentage of fat and protein content may be decreased. Therefore, to explore and analyze the multi-dimensional control mechanism of controlling the formation of complex traits in livestock and

poultry and coupling them effectively is the basis for realizing the precise improvement of complex traits in livestock and poultry. Therefore, the original innovation of breeding is changing from one-dimensional control of single trait to multi-dimensional precise coupling of comprehensive traits, and in-depth research on the precise control of complex traits will lay a theoretical foundation for the interpretation of species diversity and precision breeding. The multidimensional precise coupling of comprehensive traits has become a new direction for the study of the regulatory mechanism of trait formation and molecular breeding.

(3) Future research directions and innovations

In the future, the direction of basic research on important traits of livestock and poultry mainly includes the formation and evolution mechanism of excellent germplasm resources of livestock and poultry, key genes and regulatory networks of important traits of livestock and poultry, and high-throughput functional gene mining and identification technology, etc. The main contents are as follows: ① Constructing panoramic features of the core germplasm of livestock and poultry and revealing the formation and evolution law of important traits in the process of the development of agricultural animals from wild species to local varieties and then to modern varieties. Evolutionary law, digging out the key regulatory genes for the formation of excellent traits. ② To establish a standard sample library of livestock and poultry breeds in China, and to develop high-throughput identification techniques for phenotypes and genotypes. ③ To study the biological basis for the formation of hybrid advantage in livestock and poultry for important traits such as high yield, high quality, disease resistance, high reproduction, feed conversion rate, etc., to excavate and characterize the functional genes and regulatory elements of allele-specific expression between parents and hybrids, to analyze the relationship between gene interactions and hybrid advantage and molecular regulatory mechanisms, and to elucidate the genetic and molecular mechanisms for the formation of hybrid advantage in important traits in agricultural animals. ④ Integrate phenome-gene mining-functional analysis-trait selection to deeply and systematically analyze the genetic law and formation mechanism of traits, and to improve the key theory and technology of creating excellent germplasm for livestock and poultry.

In the front of “the regulatory mechanism for the formation of important traits in livestock and poultry”, the top three countries in terms of the publication of core papers (Table 8.11) are China (29.36%), the USA (24.16%), and Italy (9.17%). Among them, the citations per paper in Canadian, Australian, and Irish articles are relatively high. In terms of the distribution of research institutions (Table 8.12), the Northwest Agriculture and Forest University, Zagazig University, and China Agricultural University have produced many core papers and cited many times. In terms of cooperation networks among countries (Figure 8.7), research cooperation among countries is more common, and cooperation among China, the USA, and Canada is relatively closer. In terms of cooperation networks among institutions (Figure 8.8), there are certain cooperation relations among these institutions. The main output countries of the citing papers are China, the USA, and Australia, with China accounting for more than 1/3 (Table 8.13). In terms of the main output institutions of the citing papers (Table 8.14), Chinese Academy of Agricultural Sciences, China Agricultural

Table 8.11 Countries with the greatest output of core papers on “the regulatory mechanism for the formation of important traits in livestock and poultry”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	96	29.36	4 197	43.72	2019.4
2	USA	79	24.16	3 766	47.67	2019.2
3	Italy	30	9.17	1 457	48.57	2019.0
4	Egypt	29	8.87	1 312	45.24	2019.0
5	Canada	28	8.56	2 016	72.00	2019.1
6	Germany	28	8.56	1 277	45.61	2019.0
7	Australia	26	7.95	1 668	64.15	2019.3
8	UK	24	7.34	926	38.58	2019.2
9	Ireland	23	7.03	1 262	54.87	2018.8
10	Brazil	23	7.03	993	43.17	2019.2

Table 8.12 Institutions with the greatest output of core papers on “the regulatory mechanism for the formation of important traits in livestock and poultry”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Northwest Agriculture and Forest University	29	8.87	1 360	46.90	2019.1
2	Zagazig University	19	5.81	939	49.42	2019.0
3	China Agricultural University	18	5.50	655	36.39	2019.2
4	University of Alberta	15	4.59	1 298	86.53	2018.7
5	Teagasc–The Agriculture and Food Development Authority	15	4.59	764	50.93	2018.9
6	Aarhus University	14	4.28	726	51.86	2018.6
7	University of Guelph	13	3.98	785	60.38	2019.4
8	Yulin University	12	3.67	564	47.00	2019.2
9	United States Department of Agriculture-Agricultural Research Service	11	3.36	645	58.64	2018.7
10	South China Agricultural University	11	3.36	447	40.64	2019.1

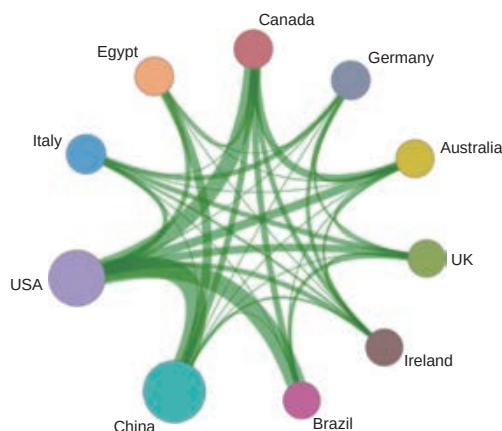


Figure 8.7 Cooperation network among major countries in the engineering research front of “the regulatory mechanism for the formation of important traits in livestock and poultry”

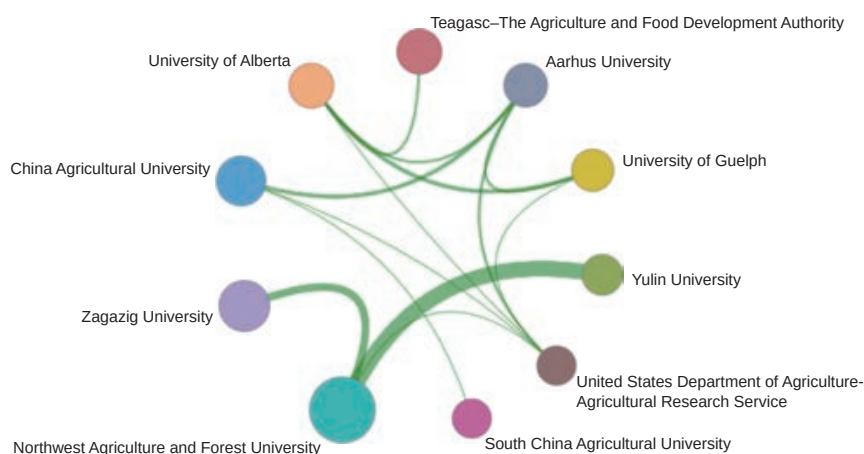


Figure 8.8 Cooperation network among major institutions in the engineering research front of “the regulatory mechanism for the formation of important traits in livestock and poultry”

University, and the Northwest Agriculture and Forest University ranked among the top three in the number of cited papers. Figure 8.9 shows the roadmap of the engineering research front of “the regulatory mechanism for the formation of important traits in livestock and poultry”.

Table 8.13 Countries with the greatest output of citing papers on “the regulatory mechanism for the formation of important traits in livestock and poultry”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	3 117	34.01	2021.8
2	USA	1 608	17.55	2021.6
3	Italy	726	7.92	2021.5
4	UK	549	5.99	2021.5
5	Brazil	536	5.85	2021.6
6	Canada	479	5.23	2021.5
7	Germany	468	5.11	2021.4
8	Australia	432	4.71	2021.5
9	Egypt	432	4.71	2021.6
10	France	414	4.52	2021.3

Table 8.14 Institutions with the greatest output of citing papers on “the regulatory mechanism for the formation of important traits in livestock and poultry”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Agricultural Sciences	431	17.39	2021.7
2	China Agricultural University	371	14.97	2021.6
3	Northwest Agriculture and Forest University	368	14.84	2021.4
4	Chinese Academy of Sciences	181	7.30	2021.7
5	Zagazig University	178	7.18	2021.4
6	United States Department of Agriculture- Agricultural Research Service	174	7.02	2021.4
7	University of Guelph	171	6.90	2021.6
8	The University of Edinburgh	157	6.33	2021.2
9	University of Sao Paulo	152	6.13	2021.4
10	South China Agricultural University	152	6.13	2021.6

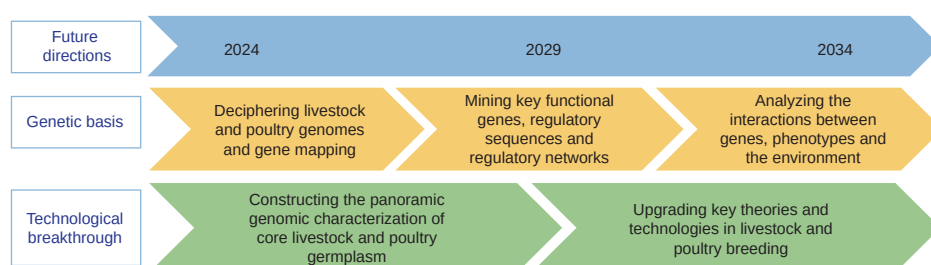


Figure 8.9 Roadmap of the engineering research front of “the regulatory mechanism for the formation of important traits in livestock and poultry”

8.2 Engineering development fronts

8.2.1 Trends in the Top 10 engineering development fronts

The top ten engineering development fronts in the agricultural field are mainly focused on artificial intelligence and green and efficient agriculture (Table 8.15). ① The front of artificial intelligence includes “crop intelligent design and synthetic biology breeding”, “pesticide big data integration and intelligent traceability”, “targeted development of markers for horticultural corps breeding based on big data”, “precision coupling of crop water-fertilizer and intelligent system and equipment”, and “intelligent aquaculture platform and equipment for deep and distant seas”. ② The front of green and efficient agriculture includes “technology for organic waste utilization and ecological management”, “the regulation of wood hierarchical structures and the fabrication of functional wood-based composites”, and “biosynthesis and efficient utilization of protein feed”. ③ The front of animal and food safety includes “the development of novel diagnostic reagents for animal diseases” and “the development of high-performance detection reagents for hazardous substances in animal-derived foods”. The core patent disclosure of the above development frontiers from 2018 to 2023 is shown in Table 8.16. The core patent of “targeted development of markers for horticultural corps breeding based on big data” has a total of 88 publications, with a citation count of 4 273 and an average citation count of 48.56, indicating that the direction of integrating big data and intelligence in the agricultural field has received widespread attention from scientific researchers in recent years. The core patent of “precision coupling of crop water-fertilizer and intelligent system and equipment” has the highest number of publications, with a total of 255. Compared to others, it has been found that there are relatively few core patents for “the development of high-performance detection reagents for hazardous substances in animal-derived foods” in recent years, and no core patents have appeared in 2023.

(1) Biosynthesis and efficient utilization of feed protein

Traditional feed protein primarily comes from plants, animal by-products, and microorganisms. These proteins can be used for livestock and poultry feed production after proper processing. With the increasing global demand for animal protein, developing efficient and sustainable feed protein resources has become necessary. The biosynthesis of feed protein is mainly based on biotechnology and fermentation techniques to convert low-value agricultural by-products, food industry waste, or specific

Table 8.15 Top 10 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations for patent	Mean year
1	Biosynthesis and efficient utilization of protein feed	29	45	1.55	2021.8
2	Crop intelligent design and synthetic biology breeding	94	288	3.06	2021.5
3	The development of novel diagnostic reagents for animal diseases	191	1 038	5.43	2021.2
4	The development of high-performance detection reagents for hazardous substances in animal-derived foods	27	64	2.37	2019.5
5	Pesticide big data integration and intelligent traceability	52	215	4.13	2021.4
6	Precision coupling of crop water-fertilizer and intelligent system and equipment	255	440	1.73	2020.8
7	Technology for organic waste utilization and ecological management	139	161	1.16	2020.9
8	Intelligent aquaculture platform and equipment for deep and distant seas	9	12	1.33	2021.9
9	Targeted development of markers for horticultural corps breeding based on big data	88	4 273	48.56	2020.7
10	The regulation of wood hierarchical structures and the fabrication of functional wood-based composites	18	20	1.11	2021.2

Table 8.16 Annual number of core patents published for the Top 10 engineering development fronts in agriculture

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Biosynthesis and efficient utilization of protein feed	1	0	2	7	11	8
2	Crop intelligent design and synthetic biology breeding	5	6	8	23	20	32
3	The development of novel diagnostic reagents for animal diseases	20	26	17	26	29	73
4	The development of high-performance detection reagents for hazardous substances in animal-derived foods	10	7	2	2	6	0
5	Pesticide big data integration and intelligent traceability	3	2	12	9	9	17
6	Precision coupling of crop water-fertilizer and intelligent system and equipment	35	27	41	46	64	42
7	Technology for organic waste utilization and ecological management	16	21	16	23	34	29
8	Intelligent aquaculture platform and equipment for deep and distant seas	0	0	1	2	3	3
9	Targeted development of markers for horticultural crops breeding based on big data	10	10	18	19	18	13
10	The regulation of wood hierarchical structures and the fabrication of functional wood-based composites	2	0	3	4	6	3

culture media into high-quality proteins. Microbial fermentation is a key technology during this process, where specific strains can transform low-value carbon and nitrogen waste into microbial protein (also known as single-cell protein). These proteins not only have a balanced amino acid composition but are also produced in an environmentally friendly and efficient manner. In terms of feed protein utilization, the quality of the feed protein and the digestibility and absorption efficiency in livestock are critical. By optimizing feed processing techniques, such as extrusion, enzymatic hydrolysis, and fermentation, the digestibility and bioavailability of proteins can be enhanced. Additionally, the inclusion of certain enzyme preparations, probiotics, or organic acids in the feed protein can further improve its digestion and absorption in livestock and poultry, and reduce ammonia emissions from animals. Furthermore, by calculating the accurate nutritional needs of livestock and scientifically utilizing proteins from different sources, feed utilization efficiency can be effectively increased, and feeding costs can be thereby reduced. Therefore, with the continuous development of molecular biology, genetic engineering, and precision nutrition in feed, the technology for the biological synthesis and efficient utilization of feed protein will be further enhanced. This advancement not only helps reduce feed costs but also decreases reliance on natural resources, driving the livestock industry toward a more sustainable and environmentally friendly direction.

(2) Crop intelligent design and synthetic biology breeding

Crop intelligent design and synthetic biology breeding technology refers to the reconstruction and design of crop gene sequences and metabolic pathways based on multi-disciplinary knowledge including computer science, information technology and biology, creating new concepts and techniques for variety breeding at the genetic and molecular levels. This technology mainly decodes and analyzes multi-omics data of crops such as transcriptome, genome and epigenome to conduct whole-genome prediction and design of crop traits, in order to excavate superior alleles from germplasm resources and guide precision hybrid breeding of crops; or design non-natural superior alleles or functional nucleic acid/protein components to guide molecular-assisted breeding of crops and realize precise design and development of new varieties. In recent years, with the accumulation of multi-disciplinary knowledge such as computer science, information technology and biology, this technology has developed rapidly. Countries around the world have introduced relevant development plans and focused on supporting related research and development projects. Meanwhile, many international seed companies have realized intelligent upgrading of breeding technologies through

integration of large data, machine learning, whole genome selection, gene editing and other technologies. In the next 5–10 years, with the maturation of frontier technologies such as artificial intelligence and gene editing, crop intelligent design and synthetic biology breeding technology will make new progress in targeted design of superior alleles, design of biological components and realization of “intelligent breeding” new patterns, becoming a major driving force for advancement of agricultural science and technology. This technology has become an important field of international agricultural science and technology competition.

(3) The development of novel diagnostic reagents for animal diseases

The livestock industry accounts for over 30% of the total agricultural output value in China, playing a vital role in the national economy by stabilizing urban and rural food prices and increasing farmers’ incomes. However, as the livestock industry grows rapidly, the number of animal diseases has also increased. The rising risk posed by the introduction of various foreign animal diseases has become increasingly prominent, and the emergence and re-emergence of zoonotic diseases pose serious threats to public health, impacting people’s health and social stability. In this challenging context of animal disease prevention and control, timely diagnosis, rapid detection, and effective monitoring and purification of animal diseases are paramount to ensuring the safety of livestock production, animal-derived food safety, and public health. However, the innovation in animal disease diagnostic technology and product development is insufficient. The stability of production processes is relatively poor, industrialization is underdeveloped, and there is a significant gap compared to international standards. Therefore, it is essential to improve national and industry standards for animal disease diagnostic testing technology and related technical specifications, establish a repository of reference materials for major animal diseases and zoonotic diseases, and enhance the introduction and development of diagnostic technologies such as pathology, serology, molecular biology, and pathogen isolation and identification. This will guide the industrialization of animal disease diagnostic reagents, achieving the goals of rapid, accurate, on-site, multi-component, and high-throughput diagnosis and detection. Such advancements are of great significance for disease prevention and control, public health, and international trade.

(4) The development of high-performance detection reagents for hazardous substances in animal-derived foods

China is one of the countries with high producer, consumer, and trader of animal derived food. Food safety is crucial to the national economy, people’s livelihoods, social harmony, and people’s health, and is an essential component of advancing the Healthy China. As the government, industry and consumers pay attention to the safety of animal-derived food continuously and the further development of international food trade, the food safety limit standards are becoming increasingly strict, and the regulatory requirements and technical barriers are getting higher, which put forward higher requirements on the detection efficiency and detection performance. Therefore, it is necessary to create high-performance detection reagents for hazardous substances to meet the high requirements of animal-derived food safety testing. For chemical and biological hazard factors such as veterinary drugs, illegal additives, mycotoxins and foodborne microorganisms in animal-derived food, high-performance biometric materials based on gene editing and protein engineering should be developed. New probes such as quantum dots, metal-organic frameworks, nano-enzymes and other new type’s probes should be developed. Low-cost, portable and automated testing equipment has to be developed based on high-throughput detection modes such on micro-arrays, micro-fluidics, and nanochips and so on. These could help to realize real-time monitoring of the whole chain of animal-derived food from farm to table, production to processing, storage to circulation to ensure food safety.

(5) Pesticide big data integration and intelligent traceability

Pesticides are crucial strategic materials for ensuring stable and high yields in food production, serving as the material foundation for strengthening the strategy of “technology-based grain storage”. However, the use of pesticides also raises issues such as pest resistance, ecological safety, and food security. Pesticide big data integration and intelligent traceability involve using modern information technology to systematically consolidate, analyze, utilize, and track the vast amounts of data generated during the production, distribution, and application of pesticides. This process establishes a comprehensive data chain for the entire lifecycle of pesticide usage, enabling scientific monitoring and intelligent management throughout the entire pesticide process. It facilitates better tracking of changes in pesticide residues in agricultural products, understanding of pesticide application practices

and effects, and guides farmers towards rational pesticide use. Consequently, it mitigates the emergence and progression of pest resistance, reduces potential risks to environmental and food safety posed by pesticides, and promotes the application and development of agricultural intelligence risk assessment technologies, achieving safe and controllable pesticide use. The implementation of pesticide big data integration and intelligent traceability propels agricultural production towards greater intelligence and precision, laying a solid foundation for the scientific management and safe use of pesticides. It also assists regulatory authorities in gaining a deeper understanding of pesticide production, sales, and usage, enabling timely identification and resolution of issues, enhancing regulatory efficiency, and holding significant implications for the development of the pesticide industry, food security, environmental safety, and health safety.

(6) Precision coupling of crop water-fertilizer and intelligent system and equipment

The precise coupling of crop water and fertilizer is a modern agricultural technology that aims to improve crop yield, improve quality, save resources and protect the environment by accurately controlling irrigation water, fertilization type, fertilization amount and fertilization time according to the water and nutrient demand characteristics of different crops and soil environmental conditions, so as to achieve the best coordination of water and nutrients in the process of crop growth and development. Water and fertilizer coupling emphasizes the accuracy and coordination of water and nutrient management. It aims to optimize the water and fertilizer management system and fully tap the crop production potential of saving water and saving fertilizer by studying the water and nutrient demand characteristics of different crops at different growth stages. Intelligent system and equipment refer to intelligent equipment and systems that integrate functions such as perception, analysis, decision-making, and execution to build an intelligent decision support system for crop water and fertilizer management. According to the needs of crop growth and soil environmental conditions, the optimal water and fertilizer management scheme is automatically generated to realize the automation and precision of water and fertilizer management. These systems and equipment usually include soil moisture and nutrient detection equipment, intelligent irrigation control systems and precision fertilizer applicators based on big data and artificial intelligence technology, etc. Through the Internet of Things, big data, artificial intelligence and other advanced technologies, real-time monitoring, data analysis, decision support and precise regulation of crop growth environment will be realized.

(7) Technology for organic waste utilization and ecological management

The utilization of organic waste resources and ecological environmental management is crucial for agricultural sustainable development. Technologies for the utilization of organic waste resources and ecological environmental management aim to transform organic waste into fertilizers, energy, materials, feed, and substrates while simultaneously reducing waste volumes, and environmental emissions. These technologies mainly include aerobic or anoxic composting, anaerobic digestion for methane production, anaerobic digestion for acid production, hydrothermal carbonization etc. Non-powered and oxygen-composting technology, manure and manure storage and fermentation stabilization technology, solid and liquid manure on-site nearby utilization technology and manure inoculation to strengthen high-temperature composting technology, manure micro-oxygen assisted biological fermentation technology, commercial organic fertilizer precision application technology, straw on the basis of meeting fertilizer and feed, high-value dyeing, materialization, and creation of chemicals from straw represent the future direction of organic waste utilization. The high-value decentralized community-level processing technology for kitchen waste is also a part of future development of organic waste utilization.

(8) Intelligent aquaculture platform and equipment for deep and distant seas

Aquaculture provides people with high-quality protein and fat, and the sustainable development of the aquaculture industry is an important foundation for ensuring food security. Deep-sea aquaculture is one of the important ways to expand aquaculture space and reduce the burden of nearshore environmental pollution. However, issues such as the low level of industrial organization, high investment risks, and insufficient intelligence in aquaculture equipment still need to be addressed. The development of mechanized, automated, information-driven, and intelligent deep-sea aquaculture platforms and equipment, as well as the creation of cost-effective, safe, and reliable fisheries equipment, will provide the hardware support needed for the growth of the

deep-sea aquaculture industry. In terms of theoretical research and supporting technologies, there is a lack of integration in smart and precise feeding technology, aquaculture tailwater treatment technology, and mechanized harvesting technology. Additionally, data model research on the economic and ecological benefits of aquaculture is insufficient. Regarding species selection, there are few available varieties, some overlap with nearshore species, and certain species rely on imported broodstock, leaving much room for improvement. With breakthroughs in intelligent technology, artificial intelligence, big data technology, cloud control, and green energy, along with the successful breeding of new species adapted to deep-sea aquaculture platforms and the improvement of equipment support capabilities and complementary systems, fully automated deep-sea intelligent aquaculture platforms and equipment are likely to become a reality. The research outcomes in this field will undoubtedly provide crucial guidance and technical support for deep-sea aquaculture.

(9) Targeted development of markers for horticultural crops breeding based on big data

With the rapid development of bioinformatics and big data technology, using big data to develop breeding markers for horticultural crops has become a key strategy in modern breeding. Big data in horticultural breeding mainly comes from various dimensions such as genomics, phenomics, environmental data, and multi-omics data. The development of breeding markers depends on the precise analysis of complex traits, involving factors like multi-gene regulation and gene-environment interactions. Big data technology, through high-throughput sequencing and omics analysis, provides vast amounts of genetic, physiological, and environmental information, helping to identify genes or markers related to important traits. Big data-driven marker development can be implemented through several approaches: ① Using methods like genome-wide association studies (GWAS), genomic selection (GS), expression quantitative trait loci (eQTL) analysis, and metabolite-GWAS (mGWAS) to pinpoint key genes or markers influencing crop quality, resistance, and adaptability. ② Building a saturated genetic variation database to generate large-scale mutant materials, linking phenotypic variation with mutated genes, and establishing a clear functional gene resource. ③ Integrating multi-layer data from genomics, transcriptomics, and metabolomics to identify key genes and metabolic pathways, deepening the understanding of the molecular mechanisms behind trait formation, and aiding in the development of functional markers. ④ Utilizing machine learning algorithms to mine hidden patterns and relationships from big data, predicting genotype-phenotype associations, and by incorporating environmental data, capturing nonlinear relationships beyond genotype and phenotype, thus improving prediction accuracy. The deep integration of artificial intelligence with marker development enables automated, intelligent analysis of vast data sets, identifying key information nodes, optimizing breeding strategies, and building intelligent breeding systems. The fusion of big data with existing marker-assisted breeding systems will lay a solid foundation for intelligent, data-driven modern breeding.

(10) The regulation of wood hierarchical structures and the fabrication of functional wood-based composites

China stands as a major global player in the processing and consumption of wood. In recent years, the supply-demand contradiction for high-quality wood has become increasingly prominent. The structural regulation and functionalization of wood have become an urgent necessity as a key strategy for enhancing the quality and efficiency of wood. Due to the hierarchical structures of wood, it is challenging to process it as a homogeneous material. Therefore, efficient functionalization technologies for wood should be targeted at regulation of its hierarchical structures. The hierarchical structures of wood include macrostructure, microstructure, the ultrastructure of wood cell wall, and the chemical structure of components. Traditional functionalization techniques for wood, such as physical heat treatment and chemical impregnation, are relatively singular in their targeting. The construction of functional interfaces in different levels is neglected. With the in-depth analysis of the wood supramolecular structure and the development of nanotechnology, it is now possible not only to precisely regulate the hierarchical structures of wood but also to construct new composite interfaces. This will significantly enhance the durability of wood, the performance of wood such as dimensional stability, flame retardancy, and decay resistance have been greatly improved, and new functionalities such as electromagnetic shielding, piezoelectric sensing, and efficient thermal management have been endowed to wood. Research on the regulation of wood hierarchical structures and the fabrication of functional wood-based composites will enrich the basic theory of efficient utilization of wood in China. It also provides scientific and technological support for the high-value utilization of wood and the promotion of industrial transformation and upgrading. More importantly, it holds significant scientific value and practical significance for the development of new quality productive forces and other national strategies.

8.2.2 Interpretations for three key engineering development fronts

8.2.2.1 Biosynthesis and efficient utilization of protein feed

The engineering development of “biosynthesis and efficient utilization of protein feed” is a critical research direction to address global food security, environmental needs, and sustainable animal husbandry. Traditional protein feeds like fishmeal and soybean meal face challenges such as limited resources, price fluctuations, and environmental pressures. Therefore, synthesizing new protein feeds through biotechnological means and optimizing their efficient utilization in animals has become a research hotspot in modern agriculture and bioengineering. Current research frontiers include microbial fermentation, insect protein production, single-cell protein (SCP), and cultured meat. These technologies not only reduce reliance on traditional protein sources but also provide a stable and efficient protein source for the livestock industry, increasing production efficiency. Furthermore, they help reduce land and water resource consumption in traditional protein feed production, lowering environmental burdens and reducing the carbon footprint of farming operations. Since the mid-20th century, microbial fermentation technology has been introduced into protein feed production, enabling the large-scale production of SCP. Subsequently, insect protein, due to its efficient protein conversion and rich nutritional value, has become a focus of alternative protein research. In recent years, with the rapid development of synthetic biology and genetic engineering, scientists have begun using gene editing to design microbial strains that efficiently synthesize proteins and have developed a series of new protein feeds. Significant progress has been made in protein feed biosynthesis technology, such as producing SCP through yeast and *Escherichia coli* and insect protein production systems like black soldier flies. Moreover, the development of cultured meat is another significant breakthrough in the protein feed field, allowing the direct production of proteins for animal and human consumption through cell culture techniques. The main research directions in protein feed biosynthesis and efficient utilization include ① microbial protein production, ② insect protein development, ③ SCP, and ④ efficient utilization of protein feed.

Core patents related to “biosynthesis and efficient utilization of protein feed” are mainly produced by the countries listed in Table 8.17. The USA ranks first with 16 core patents, accounting for 55.17%; China ranks second with 6 patents, accounting for 20.69%; Canada ranks third with 3 patents, accounting for 10.34%. Other countries, such as Republic of Korea, Denmark, and Singapore, have 2, 1, and 1 patents, respectively. There are no cooperation relationships between the USA, Canada, Denmark, Republic of Korea, Singapore, and China. In terms of major institutions (Table 8.18), Prairie AquaTech LLC has the most core patents with 12, accounting for 41.38%, followed by the South Dakota Board of Regents with 4 patents, accounting for 13.79%. Nanjing Zhirun Biotechnology Co., Ltd. in China ranks third with 2 patents, accounting for 6.9%. The most cited patents are from Prairie AquaTech LLC (60.00%), followed by the South Dakota Board of Regents (35.56%) and Denmark’s Novozymes BioAg Co., Ltd. (11.11%). The patents of Nanjing Zhirun Biotechnology Co., Ltd., Angel Yeast Co., Ltd., and the China Food Fermentation Industry Research Institute Co., Ltd. are cited at 8.89%, ranking fourth, fifth, and sixth, respectively. Figure 8.10 shows that Prairie AquaTech LLC has close cooperation with the South Dakota Board of Regents, while Angel Yeast Co., Ltd. and the China Food Fermentation Industry Research Institute Co., Ltd. have strong collaboration.

The roadmap of “biosynthesis and efficient utilization of protein feed” in next ten years is shown in Figure 8.11, which will focus on several key areas. ① Synthetic biology and genetic engineering: optimizing protein synthesis pathways in microbial strains and

Table 8.17 Countries with the greatest output of core patents on “biosynthesis and efficient utilization of protein feed”

No.	Country	Publications	Percentage of published patents/%	Citation	Percentage of citations/%	Citations per patent
1	USA	16	55.17	28	62.22	1.75
2	China	6	20.69	8	17.78	1.33
3	Canada	3	10.34	1	2.22	0.33
4	Republic of Korea	2	6.90	2	4.44	1.00
5	Denmark	1	3.45	5	11.11	5.00
6	Singapore	1	3.45	1	2.22	1.00

insects through gene editing to increase protein yield and quality. The emphasis is on developing microbial systems that efficiently utilize waste or non-food materials to reduce reliance on traditional agricultural resources. ② Multi-omics integration and metabolic engineering: using multi-omics techniques (genomics, transcriptomics, metabolomics, etc.) to analyze key regulatory mechanisms in protein synthesis, further improving and optimizing production processes. ③ Environmental protection and sustainability: focusing on developing low-carbon, low-energy protein feed production processes, promoting a circular economy, and utilizing agricultural and industrial by-products as fermentation substrates to maximize resource utilization. Future protein feed production will trend toward scale and automation, with synthetic biology advancements continuously introducing new protein sources. As global demand for environmentally friendly industries grows, green production processes will become mainstream. Feed based on microbial fermentation and insect protein will increasingly dominate the market, while cultured meat and plant-based alternatives will continue to expand their applications. The field of protein feed biosynthesis and efficient utilization has significant development potential. As technology matures and production costs decrease, these new protein feeds will gradually replace some traditional protein sources, alleviating global protein supply pressures and promoting sustainable agricultural and animal husbandry practices. Additionally, as consumer demand for green and healthy foods increases, the market acceptance and application prospects for these new protein feeds will continue to rise. The application scenarios for new protein feeds are broad, including livestock, poultry, and aquaculture, particularly in areas with limited resources or high environmental pressures. Furthermore, the development of cultured meat and plant-based products also presents new market opportunities for protein feed technology.

Table 8.18 Institutions with the greatest output of core patents on "biosynthesis and efficient utilization of protein feed"

No.	Institution	Publications	Percentage of published patents /%	Citations	Percentage of citations/%	Citations per patent
1	Prairie AquaTech LLC	12	41.38	27	60.00	2.25
2	South Dakota Board of Regents	4	13.79	16	35.56	4.00
3	Nanjing Zhirun Biotechnology Co., Ltd.	2	6.90	4	8.89	2.00
4	Smallfood Inc.	2	6.90	1	2.22	0.50
5	Novozymes BioAg Co., Ltd.	1	3.45	5	11.11	5.00
6	Angel Yeast Co., Ltd.	1	3.45	4	8.89	4.00
7	China Food Fermentation Industry Research Institute Co., Ltd.	1	3.45	4	8.89	4.00
8	Fluid Quip Technologies	1	3.45	1	2.22	1.00
9	Sophie's BioNutrients Co., Ltd.	1	3.45	1	2.22	1.00
10	Chosun University	1	3.45	0	0.00	0.00

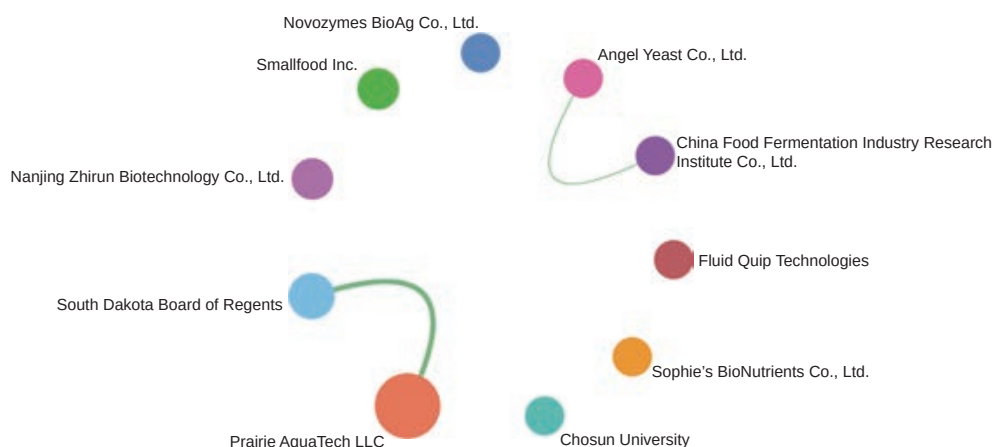


Figure 8.10 Cooperation network among major institutions in the engineering development front of "biosynthesis and efficient utilization of protein feed"

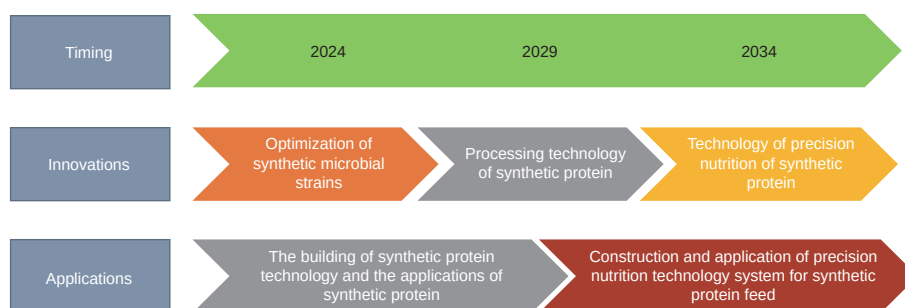


Figure 8.11 Roadmap of the engineering development front of “biosynthesis and efficient utilization of protein feed”

8.2.2.2 Crop intelligent design and synthetic biology breeding

Crop intelligent design and synthetic biology breeding refers to the reconstruction and design of crop gene sequences and metabolic pathways based on multi-disciplinary knowledge including computer science, information technology and biology, creating new concepts and techniques for variety breeding at the genetic and molecular levels. This technology mainly decodes and analyzes omics data of crops such as transcriptome, genome and epigenome to conduct whole-genome prediction and design of crop traits, in order to excavate superior alleles from germplasm resources and guide precision hybrid breeding of crops; or design non-natural superior alleles or functional nucleic acid/protein components to guide molecular-assisted breeding of crops and realize precise design and development of new varieties.

This technology has developed rapidly in recent years and played an important role in major crop variety improvement. The first case that fully utilized crop intelligent design technology for development was “Golden Rice”, which reconstructed the carotenoid synthesis pathway by introducing external genes and changing its endosperm nutrition composition. Currently, countries around the world have introduced relevant development plans and focused on supporting related research and development projects. Meanwhile, many international seed companies have realized intelligent upgrading of breeding technologies through integration of large data, machine learning, whole genome selection, gene editing and other technologies.

In the next 5–10 years, with the maturation of frontier technologies such as artificial intelligence, gene editing and single-cell sequencing, crop intelligent design and synthetic biology breeding technology will usher in new developments in three aspects. Firstly, deep learning models will play a key role in efficiently predicting functional alleles from a large number of natural variants by learning the relationship between genetic sequences and phenotypes based on germplasm resources. Secondly, with the maturation of gene editing technology, deep learning is expected to help design new superior alleles that have not been seen in nature by predicting the effects of alleles on molecular and field phenotypes, serving gene-edited breeding. Thirdly, the design of new types of biological components that do not exist in nature will become another important direction of development. For example, the application of generative models can design new antimicrobial peptides and Bt proteins, which will have great potential for the application of synthetic biology in crop breeding. In summary, the front of “crop intelligent design and synthetic biology breeding” will witness further progress in excavating germplasm resources, designing superior alleles unseen in nature and innovating new biological components in the coming decade. These advances will bring more opportunities and challenges to the agricultural sector, and continuous research and innovation are needed to promote the progress of this field.

The core patents related to “crop intelligent design and synthetic biology breeding” are mainly produced in the countries and institutions listed in Tables 8.19 and 8.20, respectively. The top three countries in terms of the number of core patent publications are China (82 patents, accounting for 87.23%), the USA (11 patents, accounting for 11.7%), and Republic of Korea (1 patent, accounting for 1.06%). There is no collaboration among these countries. The institution with the highest number of core patent outputs is Hubei University of Technology (13 patents), followed by Pioneer Hi-Bred International, Inc. and South China Agricultural University in second and third place, respectively. The top three institutions in terms of citation rate are Pioneer Hi-Bred International, Inc. (14.58%), Hubei University of Technology (12.5%), and State Grid Corporation of China (7.64%). The

institution with the highest citations per patent is the State Grid Corporation of China, with 11.00 citations, followed by Pioneer Hi-Bred International, Inc. with 10.50 citations.

Figure 8.12 depicts the roadmap of the front of “crop intelligent design and synthetic biology breeding technology”. Over the next decade, advancements are expected to be made in three key areas. Firstly, deep learning models will play a crucial role in identifying excellent allelic variations from germplasm resources. By learning the relationship between genomic sequences and phenotypes, these models can efficiently predict functional variations, discover gene variations that influence agronomic traits from a large amount of natural variations, and provide precise guidance for breeding. This approach is expected to accelerate the development of high-quality crop varieties, increase crop yield, and enhance stress resistance. Secondly, in the design of exceptional allelic variations not found in nature, the maturity of gene editing technology, together with deep learning predictions of allelic variations on molecular and field phenotypes, is expected to assist researchers in designing new exceptional allelic variations for gene editing breeding. This method will help create more market-competitive and adaptable crop varieties, promoting the modernization and sustainability of agricultural production. Thirdly, designing novel biological components that do not exist in nature will be another important development direction. For example, the application of generative modeling technology can design new biological components such as antimicrobial peptides and Bt proteins, showing significant potential for the application of synthetic biology in crop breeding. This innovation will bring new possibilities to the field of crop breeding, opening up new pathways for creating crop varieties with improved disease and pest resistance and adaptability. In summary, the future frontier of “crop intelligent design and synthetic biology breeding technology” is expected to bring exciting developments in exploring germplasm resources, designing exceptional allelic variations not found in nature, and innovating new biological components. These advancements will bring more opportunities and challenges to the agricultural sector, requiring continuous research and innovation to drive progress in this field.

Table 8.19 Countries with the greatest output of core patents on “crop intelligent design and synthetic biology breeding”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	82	87.23	232	80.56	2.83
2	USA	11	11.70	56	19.44	5.09
3	Republic of Korea	1	1.06	0	0.00	0.00

Table 8.20 Institutions with the greatest output of core patents on “crop intelligent design and synthetic biology breeding”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Hubei University of Technology	13	13.83	36	12.50	2.77
2	Pioneer Hi-Bred International, Inc.	4	4.26	42	14.58	10.50
3	South China Agricultural University	4	4.26	12	4.17	3.00
4	China Agricultural University	4	4.26	11	3.82	2.75
5	Zhejiang Lab	3	3.19	12	4.17	4.00
6	Qingdao Agricultural University	3	3.19	6	2.08	2.00
7	Nanjing Agricultural University	3	3.19	2	0.69	0.67
8	State Grid Corporation of China	2	2.13	22	7.64	11.00
9	Guangdong Oking Information Industry Co., Ltd.	2	2.13	19	6.60	9.50
10	Jiangsu Climate Center	2	2.13	12	4.17	6.00

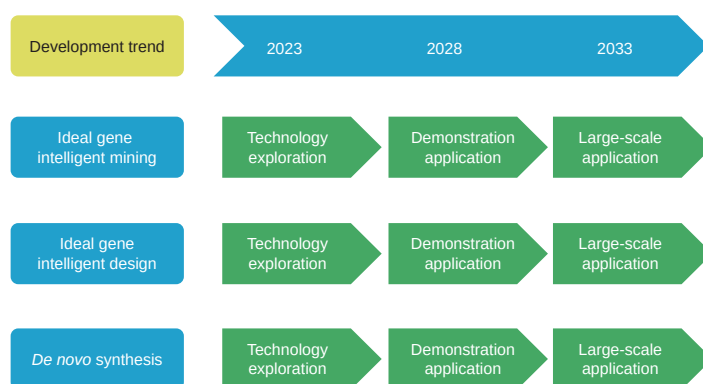


Figure 8.12 Roadmap of the engineering development front of “crop intelligent design and synthetic biology breeding”

8.2.2.3 Pesticide big data integration and intelligent traceability

Pesticides are crucial strategic production materials that ensure stable and abundant food production, serving as the material foundation for strengthening the strategy of “technology-based grain storage”. However, the use of pesticides can lead to issues such as harmful organism resistance, ecological environmental safety, and food safety. By utilizing modern information technology to integrate, analyze, utilize, and trace the massive amounts of data generated during the production, circulation, and application of pesticides, we can better understand the tracing changes of pesticides in agricultural products. This allows for a more accurate grasp of pesticide application situations and effects, thereby guiding farmers to use pesticides rationally. It reduces potential risks to environmental and food safety and promotes the application and development of agricultural intelligent risk assessment technologies, achieving safe use and controllable risks of pesticides. The implementation of big data integration and intelligent tracing of pesticides can drive agricultural production towards intelligence and precision, laying a solid foundation for the scientific management and safe use of pesticides. It also helps regulatory authorities better understand the production, sales, and usage of pesticides, allowing for timely identification and resolution of problems, improving regulatory efficiency, and significantly impacting the development of the pesticide industry, food security, environmental safety, and health safety.

The fundamental characteristics of pesticides, their target, toxicity evaluations, their target pests, action targets, toxicity evaluations, and environmental behaviors are stored in a database in structured, semi-structured, and unstructured forms, thereby constituting the big data of pesticides. This big data can be utilized in pesticide management for tracing the production, distribution, usage, and residues of pesticides, as well as forecasting the potential impacts and risks of pesticide use. The United States was the first to systematically conduct big data monitoring on a national level, with the Department of Agriculture implementing a pesticide residue monitoring program since 1991 and publishing annual reports. In 1996, the United Kingdom initiated an integrated pesticide database project and launched the PPDB in 2007. The European Union established the European Food Safety Authority in 2002 to centrally manage pesticide monitoring and other tasks, requiring all laboratory data to comply with Directive 96/23/EC and to be submitted through the Data Collection Framework platform. Although China started later, its system is large in scale. According to the “Law on Quality and Safety of Agricultural Products” and the “Measures for the Monitoring and Management of Quality and Safety of Agricultural Products”, the Ministry of Agriculture and Rural Affairs has built a pesticide residue testing system covering four levels of agricultural departments, supported by the National Risk Monitoring Information Platform for the Quality and Safety of Agricultural Products. All data are summarized according to uniform standards, with more than 12 000 annual monitoring data points for vegetable products alone. Currently, the most common models for pesticide risk assessment and intelligent traceability internationally are developed by Europe, the USA, and China. However, compared to Europe and the USA, China’s development and research in integrating big data on pesticides and intelligent traceability face issues such as lower data quality, poorer sharing, lower utilization rates, and less advanced digitalization; there is also a gap in analysis evaluation and intelligent traceability models compared to Europe and the USA.

Core patents related to “pesticide big data integration and intelligent traceability” come mainly from certain countries, institutions, which can be found in Tables 8.21 and 8.22. China ranks first in the number of disclosed core patents with 45 pieces, accounting for 86.54%; India ranks second with 2 pieces, accounting for 3.85%; while the USA, Australia, Brazil, and Germany each have one piece, ranking third (accounting for 1.92%), and there is no cooperation between these countries. Globally, 43 institutions produce core patents, among which 7 produce more than one piece, with China having 6 institutions, Beijing Uni-Star Inspection Technology Co., Ltd. and Chinese Academy of Inspection and Quarantine jointly rank first (5 pieces). The top three institutions in terms of cited proportion are Beijing Uni-Star Inspection Technology Co., Ltd. (53.49%), Chinese Academy of Inspection and Quarantine (53.49%), and Wuhan University (39.53%). The institution with the highest average citation number is Wuhan University, reaching 28.33 times. Cooperation network among major institutions is shown in Figure 8.13.

The Figure 8.14 illustrates the roadmap of the “pesticide big data integration and intelligent traceability”, which is at the forefront of technological advancements. Over the next decade, to further enhance the role of pesticide big data integration and intelligent traceability technology in promoting the development of green agriculture, it is necessary to build on the foundation of achieving interconnected data, uniform traceability standards, and norms. This can be accomplished by advancing in several key areas.

① Intelligent traceability and source tracing: By applying artificial intelligence technologies to the traceability of agricultural products, automatic identification of these products and extraction of traceability information can be achieved, providing regulatory bodies and consumers with a more intuitive and convenient way to retrieve product information. ② Data mining and prediction: Utilizing modern data mining techniques and machine learning algorithms for in-depth analysis of pesticide usage data allows for predicting trends in crop growth, pest control, and disease occurrence. This guides agricultural production decisions, reduces the misuse of pesticides, and enhances the quality of agricultural products. ③ Intelligent sensing and regulation: Combining the Internet of Things and sensor technologies to develop intelligent agricultural management systems enables real-time monitoring of farm environments and intelligent detection of crop growth conditions. This results in real-time adjustments to pesticide application rates, improving economic efficiency and environmental safety. ④ Application of blockchain technology in traceability: Exploring the use of blockchain technology to create an immutable distributed ledger of agricultural production information ensures the security and trustworthiness of production data, enhancing the transparency and traceability of the agricultural product traceability system. In summary, the integration and intelligent traceability of pesticide big data are continuously innovating and developing, aiming to achieve intelligent, precise, efficient, and safe pesticide production through technological innovation. This field still faces many challenges that require ongoing exploration and innovation to make greater progress.

Table 8.21 Country with greatest output core patents on “pesticide big data integration and intelligent traceability”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	45	86.54	194	90.23	4.31
2	India	2	3.85	0	0.00	0.00
3	USA	1	1.92	19	8.84	19.00
4	Australia	1	1.92	1	0.47	1.00
5	Brazil	1	1.92	1	0.47	1.00
6	Germany	1	1.92	0	0.00	0.00

Table 8.22 Institutions with greatest output of core patents on “pesticide big data integration and intelligent traceability”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Beijing Uni-Star Inspection Technology Co., Ltd.	5	9.62	115	53.49	23.00
2	Chinese Academy of Inspection and Quarantine	5	9.62	115	53.49	23.00
3	Wuhan University	3	5.77	85	39.53	28.33
4	Jiangsu Academy of Agricultural Sciences	3	5.77	6	2.79	2.00
5	Institute for the Control of Agrochemicals, Ministry of Agriculture and Rural Affairs	2	3.85	26	12.09	13.00
6	Bayer Crop Science	2	3.85	0	0.00	0.00
7	Dalian Shenqishijiao Network Technology Co., Ltd.	2	3.85	0	0.00	0.00
8	Rapiscan Systems Incorporation	1	1.92	19	8.84	19.00
9	Guangzhou Hoire Information Technology Co., Ltd.	1	1.92	11	5.12	11.00
10	Zhongzhui Information Technology Co., Ltd.	1	1.92	11	5.12	11.00

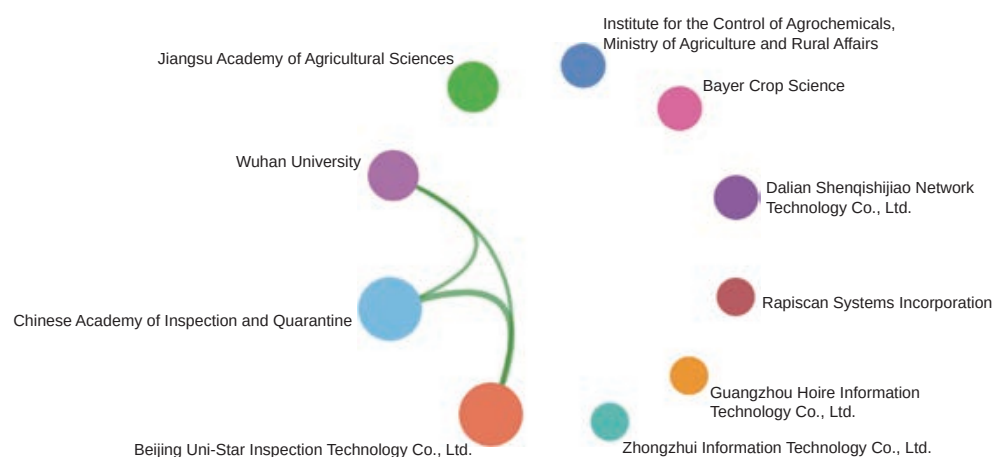


Figure 8.13 Cooperation network among major institutions in the engineering development front of “pesticide big data integration and intelligent traceability”

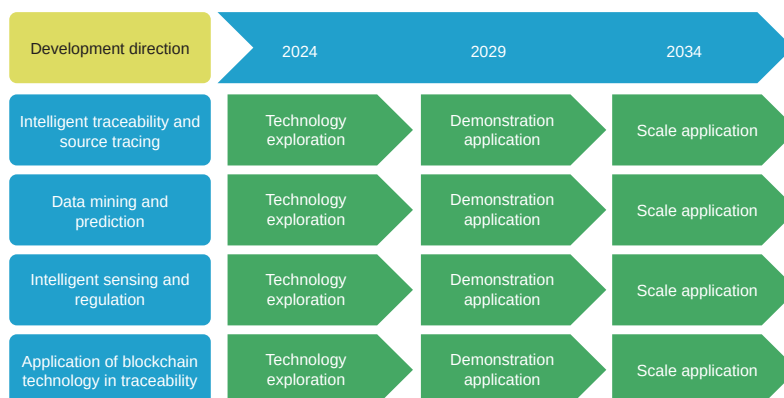


Figure 8.14 Roadmap of the engineering development front of “pesticide big data integration and intelligent traceability”

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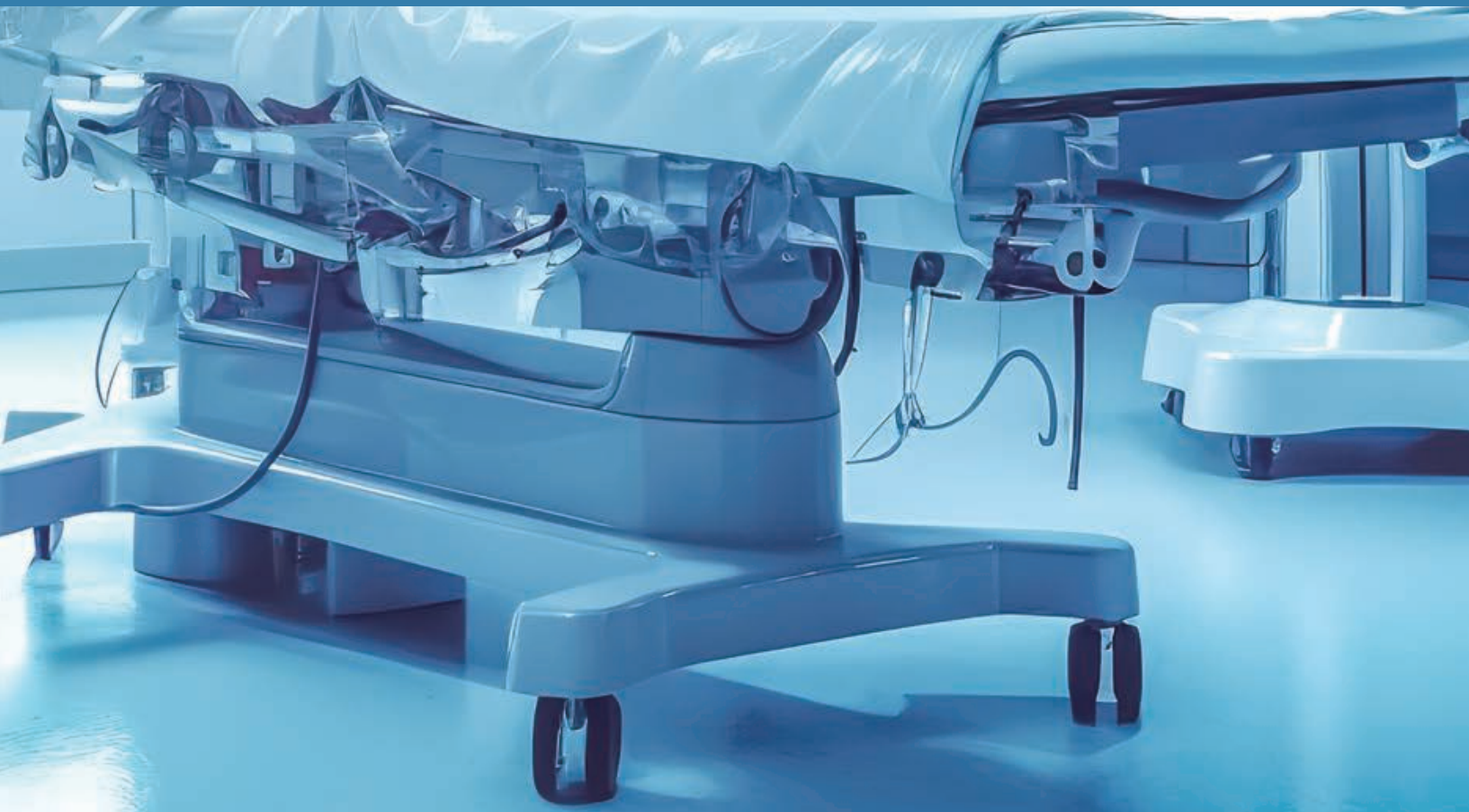
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Chapter 9 Medicine and Health Fronts



9.1 Engineering research fronts

9.1.1 Trends in the Top 10 engineering research fronts

The top ten engineering research fronts in medicine and health include basic medicine, clinical medicine, biomedical engineering, bioinformatics, immunology, and developmental biology (Table 9.1). These 10 fronts involve topics such as “human immunity: decoding, assessing, intervening, and rebuilding”, “construction and application of big data system for cohort study”, “tissue-wide cellular atlases”, “tumor immunotherapy resistance”, “epigenetic mechanisms in human tissue regeneration limitation”, “cross-species organ transplantation research”, “aging assessment and prognosis for aging-related diseases”, “life course exposure and health research”, “development of novel drugs targeting membrane proteins or nuclear receptors”, and “biosynthesis of TCM bioactive compounds”. All core papers on these topics published between 2018 and 2023 are listed in Table 9.2.

(1) Human immunity: decoding, assessing, intervening, and rebuilding

Over the past 60 years, our understanding of immunity has undergone a profound transformation. The concept has shifted from viewing immunity as “resisting external pathogen invasion” to “maintaining internal stability”. It is now recognized that T cells play a pivotal role in this process, with cellular immunity serving as the foundational element, rather than relying solely on antibodies. The thymus, a central organ in the immune system, experiences early and rapid aging, which contributes to a decline in age-related central stability, increased central immune exhaustion, and heightened morbidity and mortality rates. In pathological conditions, the persistent presence of antigens and inflammation can lead to peripheral immune exhaustion, which further aggravates central immune exhaustion, resulting in a “deadlock” in immunotherapy efforts.

The effects of radiotherapy, chemotherapy, surgery, and organ transplantation on immune function are heavily contingent upon

Table 9.1 Top 10 engineering research fronts in medicine and health

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Human immunity: decoding, assessing, intervening, and rebuilding	551	62 706	113.80	2019.6
2	Construction and application of big data system for cohort study	800	80 225	100.28	2019.6
3	Tissue-wide cellular atlases	503	64 860	128.95	2015.6
4	Tumor immunotherapy resistance	822	129 089	157.04	2019.6
5	Epigenetic mechanisms in human tissue regeneration limitation	107	14 682	137.21	2019.3
6	Cross-species organ transplantation research	314	19 375	61.70	2019.3
7	Aging assessment and prognosis for aging-related diseases	1 000	77 398	77.40	2020.3
8	Life course exposure and health research	71	8 250	116.20	2019.1
9	Development of novel drugs targeting membrane proteins or nuclear receptors	88	4 327	49.17	2019.3
10	Biosynthesis of TCM bioactive compounds	1 316	1 438	1.09	2021.0

Table 9.2 Annual number of core papers published for the Top 10 engineering research fronts in medicine and health

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Human immunity: decoding, assessing, intervening, and rebuilding	138	144	130	86	45	8
2	Construction and application of big data system for cohort study	163	243	211	138	41	4
3	Tissue-wide cellular atlases	113	143	112	93	34	7
4	Tumor immunotherapy resistance	194	212	198	153	53	12
5	Epigenetic mechanisms in human tissue regeneration limitation	36	32	20	13	5	1
6	Cross-species organ transplantation research	115	88	51	38	14	8
7	Aging assessment and prognosis for aging-related diseases	0	216	406	248	106	24
8	Life course exposure and health research	25	24	14	6	1	1
9	Development of novel drugs targeting membrane proteins or nuclear receptors	29	22	22	9	6	0
10	Biosynthesis of TCM bioactive compounds	4	8	5	1 297	2	0

the degree of immune reconstruction achieved. However, current international research predominantly focuses on animal models, singular factors, cross-sectional studies, and tissue-less investigations, which has led to lower efficiency in generating applicable knowledge and developing transformative industrial technologies.

Over the past 20 years, China's advancements in immunology have paved the way for "opening new avenues and establishing a leading position". As a result, China has become the first country globally to launch the "Human Immunity Atlas (HIA)" initiative. This initiative aims to advance biomedicine by analyzing human physiology, pathology, and disease processes through a novel paradigm of "tissue decoding, cell decoding, molecular (protein) decoding, and gene decoding" in a comprehensive chain-decoding approach. By undertaking this decoding process, we seek to establish a quantitative, graded, and staged immune assessment system, thereby providing new benchmarks for health maintenance, disease-related diagnosis, and efficacy prediction. Additionally, the initiative aspires to develop innovative treatment strategies that mitigate peripheral exhaustion by rescuing central exhaustion, addressing a critical challenge in current checkpoint therapies, where 80% of clinical immunotherapies are "bound" to tumors. Furthermore, it aims to create immune reconstruction technologies from "0 to 1" to meet the significant needs in the areas of congenital and acquired immunodeficiency diseases, chronic inflammatory diseases characterized by immune exhaustion, elderly health maintenance, and pandemic prevention and control.

(2) Construction and application of big data system for cohort study

The cohort study is a fundamental observational study design in the field of epidemiology. By tracking and comparing the differences in the incidence of specific outcomes between exposed and non-exposed groups, researchers can evaluate the causal associations between exposure factors and outcomes as well as the degree of association. The primary objective of cohort studies is to test etiological hypotheses and explore the effects of exposure factors on health, as well as to investigate the complex interactions between genes and the environment. Consequently, cohort studies serve as an essential resource for generating localized, high-quality etiological evidence. In recent years, with the support of key research initiatives in precision medicine outlined in China's 13th Five-Year Plan, the country has gradually established a series of systematic, large-scale, and comprehensive population cohorts. However, the rapid advancement of technology poses challenges to cohort research in China. Over the next five to ten years, it is crucial for China to strengthen top-level design at the national level, prioritizing support for large-scale cohorts. This includes promoting sustainable development

and establishing a sharing mechanism.

To improve the standardization of cohort research, it is crucial to first develop industry standards and data governance requirements. Introducing a multidisciplinary operation and maintenance mechanism is an inevitable trend, which should include the integration of traditional epidemiology with life sciences and information technology. This integration will facilitate the application of advanced data processing technologies, promoting the analysis of large datasets, high-throughput omics data, and medical data. Moreover, the construction of cohorts must incorporate multi-channel healthcare data and establish data interfaces across various departments. Enhancing the multichannel construction of cohort follow-up data is vital, as is the strengthening of personal privacy protections to ensure data security and legitimate usage. As a national strategic resource, cohort big data necessitates strengthened top-level system design and robust technical support to further promote the transformation of medical research results and enhance technologies for disease prevention and control.

(3) Tissue-wide cellular atlases

As the fundamental building blocks of life, cells are situated in diverse spatial locations, leading to different gene expressions that collaborate to fulfill the physiological functions of various tissues and organs. Cellular abnormalities can result in the onset and progression of a range of diseases. Therefore, it is crucial to conduct in-depth research on the spatiotemporal distribution of cellular gene expression across different tissues and organs, as this can significantly enhance our understanding of disease causation and identify key targets for exploring effective prevention and intervention strategies. With the ongoing advancements and maturation of omics sequencing technologies, including single-cell proteomics, single-cell metabolomics, and spatial transcriptomics, high-throughput sequencing has emerged as a pivotal research frontier. It allows for the detailed analysis of life sciences, the investigation of disease mechanisms, and the exploration of medical technologies through the creation of high-resolution spatiotemporal maps of cells in various tissues, ultimately leading to the development of comprehensive cell distribution maps for all human tissues. The endeavor to construct a holistic cellular map of the entire organism is a global undertaking that requires substantial research investment from numerous countries and extensive collaborative efforts between various nations and organizations. In comparison to other countries, China is currently in a phase of catching up and necessitates further research investments, increased sample resources, and enhanced institutional cooperation. By integrating higher throughput and higher resolution single-cell analysis technologies, it will be possible to produce a comprehensive spatiotemporal map of human tissue cells, whereas also exploring the practical applications of tissue cell maps in life sciences and medicine.

(4) Tumor immunotherapy resistance

Immunotherapy, which harnesses the body's own immune system to eradicate tumors, represents one of the most promising approaches to achieving complete cancer remission. However, tumors develop multiple mechanisms, including modulation of inflammatory responses, the vascular system, the tumor microenvironment, metabolic pathways, the neuroendocrine system, and the host's immune system, to diminish the effectiveness of immunotherapy. This phenomenon is referred to as tumor immunotherapy resistance, and addressing this challenge is an urgent priority in cancer treatment.

Current research on tumor immunotherapy resistance is primarily directed towards three major areas. The first focuses on tumor cell-intrinsic mechanisms, examining how the inherent characteristics of tumor cells contribute to resistance against immunotherapy. This includes studying the loss of neoantigens under immune editing pressure and defects in antigen presentation. The second area centers on the tumor immune microenvironment, investigating how this microenvironment influences immunotherapy resistance. Key factors include the absence of interferon signaling, rejection of cytotoxic T cells, enrichment of immune inhibitory factors and components, upregulation of immune evasion signals, and dysfunction in T effector cells. The third area addresses macroenvironmental suppressive factors, with research concentrating on systemic influences that contribute to immunotherapy resistance, such as immune tolerance induced by gut microbiota dysbiosis, abnormal metabolic regulation, and neuroendocrine disruptions.

In recent years, there has been significant progress in these three areas, leading to initial successes in reversing tumor

immunotherapy resistance. However, most interventions have focused solely on individual aspects of overcoming resistance, often neglecting a comprehensive, ecological perspective on tumors. Therefore, it is essential to explore the mechanisms underlying immunotherapy resistance through the lens of an integrated tumor ecosystem theory. This approach will help identify novel markers and immune regulatory molecules for predicting the efficacy of immunotherapy and will facilitate the development and expansion of innovative strategies for combination therapies.

(5) Epigenetic mechanisms in human tissue regeneration limitation

Tissue regeneration is a phenomenon observed in various living organisms, exemplified by the remarkable ability of salamanders to regenerate lost limbs. In contrast, the regenerative capacity of human tissues is limited; following an injury, tissues typically heal through fibrosis, which can result in structural and functional impairments. Epigenetics refers to heritable mechanisms that regulate gene expression without altering the DNA sequence, including DNA methylation, histone modification, and non-coding RNA activity. These epigenetic “codes” provide a crucial association between genes and phenotypes, playing a significant regulatory role in cellular development, tissue regeneration, and disease progression. Current research on the epigenetic regulation of tissue regeneration is centered on three primary areas. First, decoding the epigenetic information and dynamic changes of key genes involved in tissue regeneration, alongside associated alterations in chromosomal structure and chromatin accessibility, remains a critical research direction. Second, integrating cellular signaling networks with epigenetic modifications, chromatin remodeling, and gene expression regulation is essential for elucidating the molecular mechanisms from epigenetic control to gene expression timing and, ultimately, to tissue regeneration. Third, innovative technologies such as gene editing are being employed to rewrite the epigenetic codes of crucial genes implicated in tissue regeneration, facilitating the stable and orderly expression or silencing of these genes based on the requirements of different regeneration stages.

Overall, China has developed a robust research framework in the field of epigenetics, demonstrating the capacity to compete in cutting-edge international scientific disciplines. The *in situ* regeneration of damaged or diseased tissues resembles “post-war reconstruction”, representing a complex pathophysiological process characterized by significant research challenges, with no global breakthroughs achieved thus far. Decoding the epigenetic landscape that constrains human tissue regeneration and its “associated information” will yield valuable insights for future research endeavors in tissue regeneration.

(6) Cross-species organ transplantation research

Xenotransplantation is an emerging interdisciplinary field recognized as one of the “top 10 potential breakthrough technologies in the world” and “set to lead the next medical revolution”. Its development holds great promise in effectively addressing the prevailing shortage of organ supply in organ transplantation, significantly contributing to medical technological innovation and the protection of public health.

In 2002, the world’s first Gal knockout (GTKO) gene-edited pig was born, successfully overcoming hyperacute rejection reactions. Since then, the field of xenotransplantation has made remarkable strides. Particularly noteworthy is the year 2012, which saw the widespread application of a new generation of gene-editing technologies. These advancements have simplified the breeding of gene-edited pigs, enhanced efficiency, and significantly lowered costs, effectively ushering in a new era of xenotransplantation, with gene-edited pigs serving as potential organ donors.

In recent years, the development of xenotransplantation has progressed through three distinct phases: ① the preclinical research phase, involving pig-to-non-human primate transplantation; ② the subclinical research phase, which focuses on pig-to-brain-dead recipient transplantation; ③ the clinical research phase, including pig-to-clinical patient transplantation.

Phase one: The longest recorded survival times for recipients of kidney transplants reached 758 days; for heart transplants, the duration was 264 days; for liver transplants, it was 34 days; and for lung transplants, it was 31 days.

Phase two: In kidney transplantation, a total of nine gene-edited pig-to-brain-dead patient kidney transplants have been performed globally, with six conducted in the USA and three in China. The longest observation period post-transplant was two

months, during which good kidney function was noted, with no signs of rejection. In heart transplantation, two cases of gene-edited pig-to-brain-dead patient heart transplants were completed in the USA, both demonstrating good heart function for 3 days following the procedure and showing no indications of rejection. Additionally, in liver transplantation, one gene-edited pig-to-brain-dead patient liver transplant was performed in China, with favorable liver function observed for 10 days post-transplant and no signs of rejection. Furthermore, the USA successfully completed one case of extracorporeal liver perfusion using a gene-edited pig liver in a brain-dead patient, achieving positive results.

Phase three: In heart transplantation, 2 cases of gene-edited pig-to-heart transplants for patients with heart failure have been conducted globally, both in the USA. The first patient survived for two months but was suspected to have developed a porcine cytomegalovirus infection, which led to the rejection of the transplanted heart. The second patient lived for 40 days, during which the transplanted heart also exhibited signs of rejection. Regarding kidney transplantation, two cases of gene-edited pig-to-kidney transplants for patients with kidney failure have also been performed in the USA. In March 2024, Harvard University achieved the world's first successful gene-edited pig-to-human kidney transplant. The patient was discharged after recovery; however, he died of a heart attack 50 days later, with no evidence of rejection in the transplanted kidney. The other patient had the transplanted pig kidney removed on postoperative day 47 due to insufficient perfusion pressure, which resulted in reduced functionality, necessitating a return to hemodialysis. In liver transplantation, one case of a gene-edited pig-to-liver transplant for a patient with liver cancer has been completed in China, with the transplanted pig liver being removed on postoperative day 50.

Currently, whereas organ xenotransplantation has achieved notable successes, new challenges have emerged. These challenges require collaborative efforts from both medical professionals and scientists to enhance the short-term and long-term clinical outcomes for transplant patients.

[\(7\) Aging assessment and prognosis for aging-related diseases](#)

Aging assessment and prognosis for aging-related diseases represent a critical area in addressing the global challenge of aging. This multidisciplinary field seeks to clarify the complex mechanisms of aging whereas developing accurate quantification systems for both the aging trajectory and the prediction of aging-related disease risks. It includes not only natural physiological aging but also emphasizes the early identification and intervention in pathological aging, with the ultimate goal of promoting healthy aging. Currently, the field of aging assessment and early prognosis for aging-related diseases is advancing rapidly. To bridge the gap between aging research and clinical applications, Chinese scholars have collaboratively developed a wide range of multidimensional aging biomarkers across various tissues and organs. These biomarkers are examined at cellular, molecular, body fluid, and imaging levels, employing a cross-species, multi-scale, systematic, and high-resolution research approach. By harnessing artificial intelligence (AI) and other cutting-edge technologies, researchers have systematically characterized and defined composite clocks that reflect biological age within the Chinese population, facilitating the identification of senescent cells and the assessment of aging progression. Despite these advancements, research on aging assessment and the prognosis of aging-related diseases continues to face significant challenges. The exploration of aging biomarkers is still inadequate, and there is a scarcity of relevant indicators that denote the degenerative milestones of organs associated with the aging process. Individual heterogeneity, genetic backgrounds, and environmental variability further complicate the development of standardized measurement tools. There remains a notable gap in achieving precise, non-invasive, and real-time monitoring and management of aging.

Looking ahead, the integration of basic research with clinical applications will enhance the systematic identification and validation of aging biomarkers, leading to the development of more precise, convenient, and non-invasive tools for aging assessment. Furthermore, advanced technologies such as big data and AI will be fully leveraged to construct comprehensive aging databases and early prognosis systems based on multicenter population cohorts. This initiative aims to establish benchmarks for measuring aging, enabling real-time monitoring and remote intelligent management of the extent and rate of the aging process, as well as predicting the transition point where aging progresses into disease, thereby targeting interventions to combat aging-associated diseases. As research evolves, guidelines and strategies for aging prevention and treatment based on aging mechanisms will

gradually be developed, providing robust support for global healthy aging initiatives and the establishment of a worldwide health community.

(8) Life course exposure and health research

Life course exposure and health research studies how different environmental factors, such as physical, chemical, biological, and social environments, affect health across an individual's entire life, from birth to death. This field particularly emphasizes the short- and long-term health effects of early-life environmental exposures and adverse experiences, whereas recognizing that sensitivity to different exposure sources can vary at various life stages. The research anticipates the use of multi-omics approaches, especially exposomics, to analyze human exposure to environmental pollutants through various pathways such as air, water, food, and consumer products, as well as exposure to dietary nutrition, physical activity, lifestyle, and other factors across different stages of life. The goal is to elucidate the mechanisms through which these exposures impact biological processes. By applying life course environmental epidemiology methods and AI technologies, this research aims to develop risk assessment models for complex environmental exposures, identify critical windows of susceptibility, and explore the interactions between various environmental exposure factors. Multi-omics techniques are also employed to uncover the mechanisms of health impairment, identify potential intervention targets, and provide scientific evidence for the prevention and intervention of diseases, including chronic illnesses, adverse reproductive health outcomes, neurodegenerative diseases, and cancers.

In recent years, there has been a growing international focus on large-scale cohort studies and multi-center randomized controlled trials to examine individual life course exposure profiles, reduce exposure to environmental hazards, and assess the health impacts of these factors. Through interdisciplinary research, new biomarkers are being identified, and the mechanisms underlying the complex association between exposure and health are being explored. However, whereas life course health management is gradually gaining attention domestically, related research remains fragmented across various disciplines and lacks systematic integration and the guidance of a unified framework.

(9) Development of novel drugs targeting membrane proteins or nuclear receptors

The development of novel drugs aimed at membrane proteins and nuclear receptors is currently a prominent focus in the field of drug development. These targets hold significant strategic importance for creating effective new therapeutics. Drug development that focuses on membrane proteins involves designing agents capable of specifically binding to and regulating the functions of proteins found on cellular membranes, including G protein-coupled receptors (GPCRs), ion channels, transport proteins, and kinases. These membrane proteins are instrumental in cell signaling and substance transport, and their functional abnormalities are associated with various diseases, thereby establishing them as critical targets in drug development.

Key research directions in the creation of novel drugs targeting membrane proteins include GPCRs, ion channels, transport proteins, antibody-drug conjugates, and innovative antigen preparation strategies. Noteworthy progress has been made in the development of antibody drugs that target membrane proteins. For instance, the antibody drug Mogamulizumab, which targets GPCRs, and the antibody Erenumab, aimed at ion channels, have both received market approval. Additionally, MegaR technology has facilitated the structural analysis of small molecular weight GPCRs and their complexes with ligands or drugs, thereby accelerating the drug development process. PROTAC drugs that target membrane proteins, such as EGFR, have also entered clinical trials, demonstrating promising anti-tumor activity.

Conversely, drug development targeting nuclear receptors emphasizes receptor proteins located within the cell nucleus. When these receptors bind with specific ligands (such as hormones and vitamins), they can regulate gene expression and are involved in various physiological and pathological processes. The development of drugs targeting nuclear receptors is particularly prevalent in the treatment of prostate and breast cancers. For example, androgen receptors (AR) and estrogen receptors (ER) are crucial targets for therapies addressing prostate and breast cancers, respectively.

Throughout the process of developing novel drugs targeting membrane proteins or nuclear receptors, structural biology provides essential methodologies. Techniques in structural biology are employed to analyze the structures of these proteins, which informs

the design and development of new pharmacological agents. It is anticipated that, through such studies, an increasing number of drugs targeting membrane proteins or nuclear receptors will advance into clinical practice, ultimately offering enhanced treatment options for patients.

(10) Biosynthesis of TCM bioactive compounds

Biosynthesis of bioactive compounds from traditional Chinese medicine (TCM) is an emerging research field focused on uncovering the metabolic synthetic mechanisms of these compounds in TCM-derived plants and animals, with a particular emphasis on plants. This area of study plays a critical role in synthetic biology. Phytochemicals have historically been a significant source for innovative drug discovery globally, and TCM bioactive compounds offer a distinct advantage for drug discovery in China. Currently, TCM compounds are primarily obtained through extraction and isolation processes, which are often time-consuming, inefficient, and require extensive botanical resources. Consequently, challenges related to the availability of these compounds are impeding their development for therapeutic use. Biosynthesis presents a promising alternative approach to address these challenges. The biosynthesis of TCM bioactive compounds necessitates a comprehensive integration of multidisciplinary techniques and methodologies, which primarily include three key areas of research. Firstly, it involves establishing new analytical methods that integrate multi-omics approaches, including genomics, transcriptomics, and metabolomics. This research aims to explore innovative strategies for efficiently decoding the biosynthetic pathways of TCM bioactive compounds. Secondly, by combining insights from structural biology, computational chemistry, and machine learning, researchers can construct rational design models. This enables precise enzyme design and directed evolution, facilitating the provision of sufficient biological components for constructing efficient and intelligent biosynthetic systems. Lastly, there is a need to develop highly adaptable chassis cells, expression regulatory elements, and gene editing tools tailored for the biosynthesis of TCM compounds with diverse core structures. This effort aims to establish a universal technological platform. In recent years, this field has advanced rapidly in China, leading to a series of significant breakthroughs by Chinese scientists. However, the development of this area is relatively nascent in China, and key technological systems remain underdeveloped. As a result, China currently does not hold a competitive advantage on the global stage. Moving forward, it is essential to leverage the nation's strengths in medicinal plant resources whereas enhancing industrial promotion and application efforts. With these advancements, China is positioned to potentially lead the world in this field within the next 10 to 15 years.

9.1.2 Interpretations for three key engineering research fronts

9.1.2.1 Human immunity: decoding, assessing, intervening, and rebuilding

Immunology has undergone 2 500 years of development, with the last 60 years marking a significant acceleration in the field, characterized by a doubling of knowledge every four years that has profoundly transformed our understanding of human immunity. The traditional perspective of immunity as “resisting external pathogen invasion” has shifted to “maintaining the body’s homeostasis”. Contemporary immunology now sees cellular immunity, particularly the key role of T-cells, as its foundation, rather than relying only on antibodies. The thymus, a key organ in the immune system, experiences the fastest age-related decline, leading to decreased central homeostatic capacity, often referred to as central immune exhaustion, which correlates with increased morbidity and mortality across various health conditions.

In pathological states, the continual presence of antigens and inflammation can lead to peripheral immune exhaustion, thereby exacerbating central immune exhaustion and creating a “deadlock” in immunotherapy. The outcomes of radiotherapy, chemotherapy, surgery, and tissue or organ transplantation are heavily influenced by the extent of immune reconstruction. At the core of effective immunity lies homeostatic capacity; external and internal disturbances prompt the body to respond in ways that aim to restore this balance, which is associated with overall morbidity, mortality, and lifespan. A more profound understanding, intervention, and reconstruction of human immunity are crucial for promoting health throughout the entire lifecycle and across all

health processes.

However, current international research has predominantly centered on model organisms, isolated factors, cross-sectional studies, and tissue-less investigations, resulting in inefficiencies in generating applicable knowledge and developing transformative technologies. Over the past 20 years, China has made remarkable strides in immunology, creating the groundwork to “open new avenues and establish a leading position” through a novel, efficient, dynamic, panoramic, and cross-scale research paradigm aimed at addressing human immunity issues. In this context, the Chinese Society for Immunology has become the first organization globally to propose and initiate the “Human Immunity Atlas (HIA)”. This ambitious initiative seeks to advance biomedicine through a new paradigm including “tissue decoding, cell decoding, molecular (protein) decoding, and gene decoding” within a chain decoding framework. The objective is to conduct a comprehensive analysis of human physiology, pathology, and disease processes, ultimately innovating biomedicine with unprecedented diagnostic and therapeutic precision through the four research directions of “decoding, assessing, intervening, and reconstructing” human immunity.

Based on advances in understanding human immunity, this initiative aims to create a groundbreaking “0-to-1” immune assessment technology system. This system will provide quantitative, graded, and staged evaluations of individual immune responses, establishing new benchmarks for health maintenance, disease-associated diagnosis, and efficacy prediction. Additionally, the initiative seeks to develop novel treatment strategies that address peripheral exhaustion by targeting central exhaustion, effectively resolving critical issues in clinical immunotherapy, where 80% of checkpoint therapies are “bound” with tumors. Furthermore, the development of “0-to-1” immune reconstruction technologies is intended to address significant challenges associated with congenital and acquired immunodeficiency diseases, chronic inflammatory conditions marked by immune exhaustion, elderly health maintenance, and pandemic prevention and control. This comprehensive approach will pave the way for the emergence of three major industries: “Human Immunity Assessment”, “Human Immunity Intervention”, and “Human Immunity Reconstruction”, thus creating a new immune sector and stimulating a burgeoning immune economy, and revolutionizing the field of biomedicine with unparalleled diagnostic and therapeutic capabilities.

Although several domestic and international institutions have initiated research into human immunity decoding, there is currently no dedicated national or international academic organization focused on establishing a cohesive three-dimensional coordinate system for organ decoding, along with the development of technical standards, data standards, data processing technologies, visualization techniques, and data sharing protocols. Consequently, research results from various entities often lack corroboration. The field of human immunity decoding necessitates the creation of an array of new technologies for tissue, cell, molecular, and gene decoding, following a chain decoding approach. Addressing this challenge requires collaborative efforts across emerging fields in mathematics and informatics, grounded in process theory, which can be facilitated through further interdisciplinary integration and organized research.

It is important to note that human immunity decoding transcends the commonly used frameworks of single-cell sequencing and multi-omics research. The development of innovative chain decoding technologies is essential for comprehensive understanding. Likewise, human immunity assessment should not be conflated with existing immunological testing methods. Immunity intervention and immunity reconstruction necessitate pioneering technologies and products derived from fresh insights gained through immunity decoding.

Through research in human immunity decoding, assessment, intervention, and reconstruction, it is anticipated that within the next 3 to 5 years, new industries and economies may emerge, driven by transformative technologies, products, and globally recognized standards. These advancements are expected to result in revolutionary industrial technologies across major fields, including congenital and acquired immunodeficiency diseases, cancers, autoimmune diseases, chronic inflammatory diseases, biosafety, and critical care. Furthermore, they will facilitate reliable evaluation methods for precision diagnostics, health maintenance technologies, stem cell therapies, and traditional medicine approaches.

Currently, in the engineering research front of “human immunity: decoding, assessing, intervening, and rebuilding”, the leading

countries in terms of core papers are the USA, China, and Germany (Table 9.3). Notably, China represents 25.41% of the papers published, establishing itself as a key player in this research area. The collaboration networks among these major countries highlight strong partnerships, particularly between China and the USA (Figure 9.1).

The top ten institutions producing core papers on “human immunity: decoding, assessing, intervening, and rebuilding” are primarily located in the USA, China, and Netherlands (Table 9.4). The leading institutions include Harvard University, Chinese Academy of Sciences, and University of California, San Francisco. The collaboration network among these significant institutions illustrates ongoing cooperative efforts among national research entities (Figure 9.2).

Implementing organized research programs at both the national and international levels is essential. Such initiatives not only establish unified standards but also enhance the efficiency of research and the reliability of emerging knowledge. It is anticipated that similar research organizations will arise in economically developed countries within the next five years. Fundamental to these advancements are organizational decoding and cellular decoding technologies, along with informatics analysis based on process theory and chain decoding. We expect that new process theories and decoding technologies will emerge over the next 5–10 years. The translation of technology into practical applications will be a significant avenue for development. Alongside traditional medical devices and biomedicine, we can expect to see the introduction of innovative products such as electronic drugs, microfluidic chips, organ-on-a-chip systems, and on-demand organ manufacturing utilizing 3D printing technology (Figure 9.3).

Table 9.3 Countries with the greatest output of core papers on “human immunity: decoding, assessing, intervening, and rebuilding”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	219	39.75	27 088	123.69	2019.6
2	China	140	25.41	17 978	128.41	2019.9
3	Germany	49	8.89	5 374	109.67	2019.7
4	Italy	45	8.17	4 866	108.13	2019.7
5	Netherlands	44	7.99	5 284	120.09	2019.3
6	UK	43	7.80	6 208	144.37	2019.5
7	France	34	6.17	4 592	135.06	2019.7
8	Australia	27	4.90	3 113	115.30	2019.2
9	Canada	27	4.90	2 640	97.78	2019.2
10	Switzerland	24	4.36	2358	98.25	2019.4

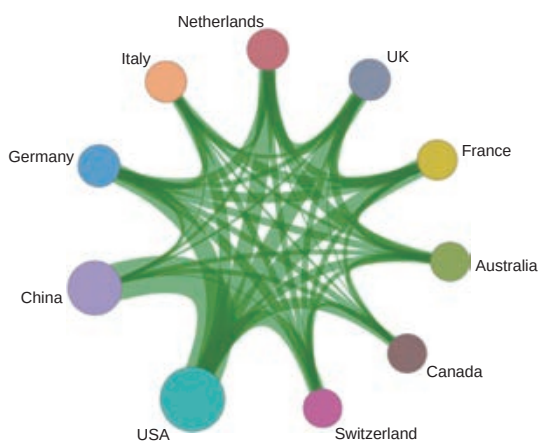


Figure 9.1 Collaboration network among major countries in the engineering research front of “human immunity: decoding, assessing, intervening, and rebuilding”

Table 9.4 Institutions with the greatest output of core papers on “human immunity: decoding, assessing, intervening, and rebuilding”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	31	5.63	3 652	117.81	2019.9
2	Chinese Academy of Sciences	22	3.99	2 601	118.23	2020.0
3	University of California, San Francisco	14	2.54	1 442	103.00	2019.4
4	Sun Yat-sen University	12	2.18	1 386	115.50	2019.5
5	University of Pennsylvania	12	2.18	1 367	113.92	2019.1
6	Third Military Medical University	11	2.00	2 789	253.55	2020.1
7	National Cancer Institute	11	2.00	885	80.45	2019.4
8	Huazhong University of Science and Technology	10	1.81	1 141	114.10	2020.1
9	Leiden University	10	1.81	1 031	103.10	2019.4
10	University of California, San Diego	9	1.63	1 568	174.22	2020.7

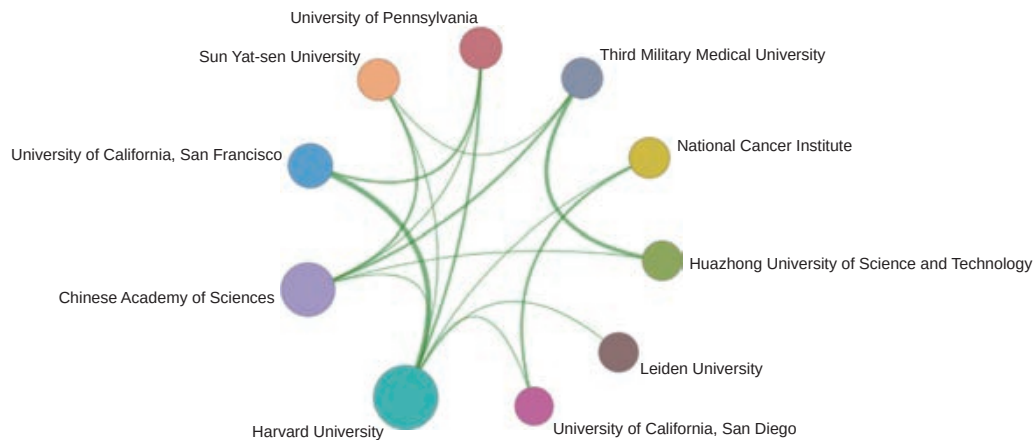


Figure 9.2 Collaboration network among major institutions in the engineering research front of “human immunity: decoding, assessing, intervening, and rebuilding”

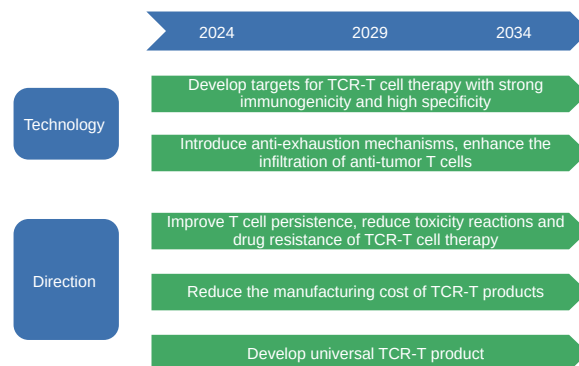


Figure 9.3 Roadmap of the engineering research front of “human immunity: decoding, assessing, intervening, and rebuilding”

9.1.2.2 Construction and application of big data system for cohort study

The cohort study is one of the fundamental observational study designs in epidemiology. Its primary purpose is to track, observe, and compare the differences in the incidence of specific outcomes between exposed and non-exposed groups. Researchers then assess the causal association between exposure factors and outcomes, along with the degree of association. Based on the subject matter, cohort studies can be categorized into three main types: natural population cohorts, special disease cohorts, and special population cohorts (including birth cohorts). Each type of cohort focuses on different health outcomes. For instance, a natural population cohort examines a natural population within a specific administrative region, typically with the aim of testing etiological hypotheses and exploring the pathogenic effects of harmful exposures. In contrast, a special disease cohort includes subjects with specific diseases and integrates clinical diagnosis and treatment information to investigate the mechanisms of morbidity, influencing factors, and drug efficacy associated with the disease. Meanwhile, a birth cohort gathers health-related data from early life and continuously monitors health outcomes during embryonic development, the fetal period, infancy, and early childhood. This approach explores the potential effects of environmental and behavioral factors in early life on parental reproduction, as well as the immediate and long-term health of offspring.

With advancements in information technology and big data, the efficiency of cohort research in data collection, storage, and analysis has significantly improved. The research paradigm has gradually shifted from the traditional “one cause versus many effects” etiological framework to a more complex “many causes versus many effects” exploration. The application of cohort studies has expanded beyond the investigation of single causes, now extending to gene-gene interactions, gene-environment interactions, multi-temporal biomarker analysis, comorbidity pattern recognition, network prediction, and other sophisticated areas of research.

Given its pivotal role in etiological research, the cohort study has gained international recognition as a method for examining the association between environmental and genetic risk factors and disease outcomes. As such, it serves not only as a critical platform for translational medicine research but also as an essential foundation for health decision-making. Its implications are far-reaching, impacting both National Health Strategy and National Security Strategy.

In recognition of the unique characteristics of the population and the critical importance of safeguarding national genetic resources, Western developed countries have established substantial national population cohorts under government leadership. Notable examples of representative large cohorts include the European Prospective Investigation into Cancer and Nutrition, which includes ten countries in Europe (EPIC, 521 000), the NIH-AARP Diet and Health Study (NIH-AARP, 566 000) in the USA, the UK Million Women Study (MWS, 1 300 000) and the UK Biobank (UKB, 498 000). Additionally, the All of Us initiative, targeting one million American residents, is a significant component of the Precision Medicine Program in the USA. The successes of these initiatives underline the pivotal role that large population cohorts can play in advancing comprehensive national medical research. Such efforts are expected to yield robust research evidence (international developments) that will inform and transform health policy and clinical practice.

Cohort studies in China commenced later than those in other countries and initially exhibited characteristics of regional dispersion, small scale, and brief follow-up periods. However, in recent years, bolstered by key research projects aligned with the 13th Five-Year Plan for precision medicine, China has gradually developed a more systematic and extensive array of population and specialty disease cohorts. This includes a nationwide natural population health cohort, as well as major disease-specific and rare disease clinical cohorts, collectively including millions of individuals. With the support of national policies and funding, the scale, quantity, and pace of cohort study development in China have increased significantly. Nevertheless, as technological advancements progress rapidly, cohort studies in China now face challenges in adapting research models. Key considerations include strengthening top-level design, ensuring the quality of cohorts, effectively integrating information technology, and facilitating a data-sharing mechanism to break down existing barriers.

Currently, the USA, China, and Germany rank as the top three countries in terms of core paper on “construction and application of big data system for cohort study”. Among them, China, contributing to 27.75% of the published papers, stands out as one of the leaders in this pioneering field (Table 9.5). From the perspective of cooperation networks among major countries, the top ten countries have close cooperation with each other (Figure 9.4).

The leading institutions in terms of core papers on “construction and application of big data system for cohort study” are predominantly from the USA, China, the UK, and Sweden. Notably, the top three institutions are Harvard University, Chinese Academy of Sciences, and Stanford University (Table 9.6). The collaboration network among the major institutions demonstrates strong cooperation between institutions in the USA and China, with some interactions among other institutions (Figure 9.5).

Table 9.5 Countries with the greatest output of core papers on “construction and application of big data system for cohort study”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	387	48.38	43 308	111.91	2019.5
2	China	222	27.75	20 839	93.87	2019.7
3	Germany	95	11.88	12 469	131.25	2019.7
4	UK	92	11.50	12 369	134.45	2019.8
5	Netherlands	69	8.62	9 194	133.25	2020.1
6	Republic of Korea	63	7.88	6 061	96.21	2019.7
7	Italy	59	7.38	7 267	123.17	2019.9
8	Canada	55	6.88	6 887	125.22	2019.7
9	Switzerland	48	6.00	5 865	122.19	2019.6
10	Japan	42	5.25	5 433	129.36	2019.4

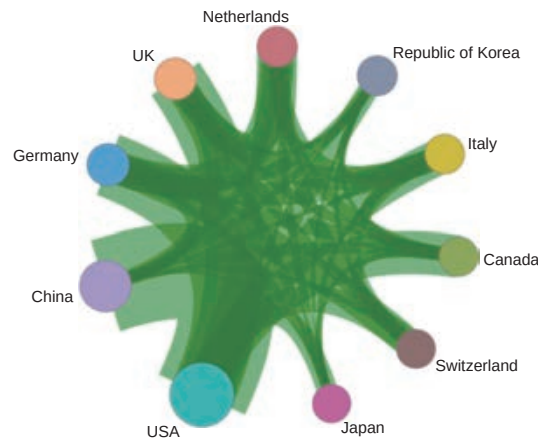


Figure 9.4 Collaboration network among major countries in the engineering research front of “construction and application of big data system for cohort study”

Table 9.6 Institutions with the greatest output of core papers on “construction and application of big data system for cohort study”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	59	7.38	9 305	157.71	2019.4
2	Chinese Academy of Sciences	47	5.88	4 314	91.79	2019.7
3	Stanford University	37	4.62	4 986	134.76	2019.3
4	Sun Yat-sen University	36	4.50	4 413	122.58	2019.9
5	Karolinska Institute	21	2.62	3 196	152.19	2019.7
6	Mayo Clinic	21	2.62	2 798	133.24	2019.8
7	University College London	20	2.50	4 867	243.35	2019.7
8	University of California, San Francisco	20	2.50	4 214	210.70	2019.2
9	Columbia University	20	2.50	2 086	104.30	2019.0
10	Brigham and Women's Hospital	20	2.50	1 810	90.50	2019.4

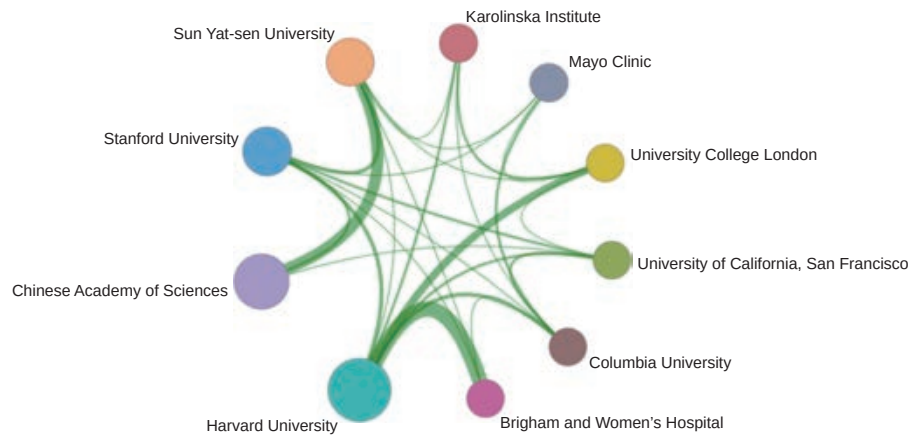


Figure 9.5 Collaboration network among major institutions in the engineering research front of “construction and application of big data system for cohort study”

In the next 5–10 years, large scale cohorts in China will face the following challenges and breakthroughs in their construction and application:

- 1) Promoting top-level overall design at the national level: Due to the varying objectives of cohort studies and the significant duration and expense associated with them, existing cohort studies in China currently lack systematic guidance and long-term developmental planning at the national level. The landscape of cohort construction is characterized by a plethora of “many, small, scattered and chaotic” studies, which often leads to redundant efforts and a tendency to follow trends without substantial justification. Consequently, formulating a sustainable development strategy for large cohorts has proven difficult. It is recommended that national authorities enhance guidance and encourage the construction of cohorts, particularly those that are large-scale and demonstrate significant value. Prioritizing information technology resources and capital investment is essential for establishing a streamlined and effective sharing mechanism, ultimately promoting the sustainable development of cohort construction and the transformation of its applications.
- 2) Promoting the construction of cohort standardization at the disciplinary level: Due to the diverse characteristics of cohort populations, there is a lack of uniformity in operational methods, measurement techniques, reference standards, and implementation protocols for exposure and results. This inconsistency leads to relatively dispersed cohorts, with independent data structures that cannot be directly integrated, thereby limiting the effectiveness and efficiency of collaborative cohort research. Therefore, the establishment of industry standards and data governance requirements in the field of cohort research is essential. Developing standards or expert consensus for specific disease cohorts, birth cohorts, and population cohorts will facilitate standardization efforts in China. Furthermore, cohort studies should also contribute insights to other areas of health, following the standardization paradigm outlined by the Genome Standards Consortium (2016) and the International Organization for Standardization (ISO).
- 3) Introduction of multi-disciplinary operation and maintenance mechanism: With the rapid advancements in life sciences and modern informatics technology, linking cohort data with high-throughput omics data, medical big data, and other datasets has emerged as a new direction for large cohort studies. High-throughput and multi-omics data provide more comprehensive and efficient evidence for the etiological analysis of complex diseases. However, storing, cleaning, and analyzing multi-dimensional big data necessitates advanced processors, substantial memory, sophisticated algorithms, and cloud computing resources. Therefore, the construction and operation of cohorts must incorporate expertise from bioinformatics, information technology, AI, and other relevant domains to effectively process cohort data using the latest information technologies. Additionally, it is essential to establish a multi-dimensional evaluation system that engages professionals from various disciplines.

4) Breaking the data island: Improving the follow-up rate of cohort studies is a fundamental objective in cohort construction. The effectiveness and accessibility of a comprehensive medical big data system will directly influence the sustainable development of large cohort studies in the future. During the follow-up phase, researchers can obtain follow-up events from organizations such as the Health and Health Commission, medical insurance departments, and others. However, the collection of follow-up data is significantly hindered by information silos resulting from the disparate management practices across various hospitals. To address these challenges, we should consider selecting a high-quality, large population cohort for a pilot project aimed at enhancing data integration between disease control registration systems and the healthcare network. This initiative should promote the establishment of an open-sharing system for medical big data. Furthermore, open sharing should be established as a key criterion in the construction and evaluation of the registration system, which can ultimately facilitate the widespread accessibility and sharing of medical big data in China.

5) Legal and ethical norms and systems: The processes of data storage, sharing, analysis, and mining within large cohorts must prioritize personal information rights and privacy. There is an inherent risk of infringing on private rights and potential threats to data security. In 2019, China promulgated the Regulations on the Management of Human Genetic Resources, followed by the promulgation of the Rules for the Implementation of these Regulations in June 2023, marking an exploratory effort to regulate the safety and ethics surrounding genetic data. Moving forward, it is essential to further refine the supervisory mechanisms and enhance legal frameworks for the classified protection of data. The rights and responsibilities concerning data mining, storage, transmission, publication, and secondary utilization must be clearly defined, with a particular emphasis on strengthening the protection of personal privacy. Cohorts serve as a vital strategic resource for the nation, facilitating the integration of regional cohort data. This system enables multi-time and multi-level data convergence, efficient storage, secure management, and seamless sharing and analysis of cohort information. The application of cutting-edge research and development within cohort datasets is a top priority for constructing a national cohort system. Ultimately, cohort studies offer extensive data resources and diverse research platforms for medical research (Figure 9.6). With the establishment of a national cohort system and collaborative participation across various disciplines, there is a strong expectation to drive the transformation and application of foundational medical research results into public health initiatives and clinical practices, thereby enhancing disease prevention and control technologies. This initiative aims to foster healthy development and achieve the ambitious vision of a Healthy China.

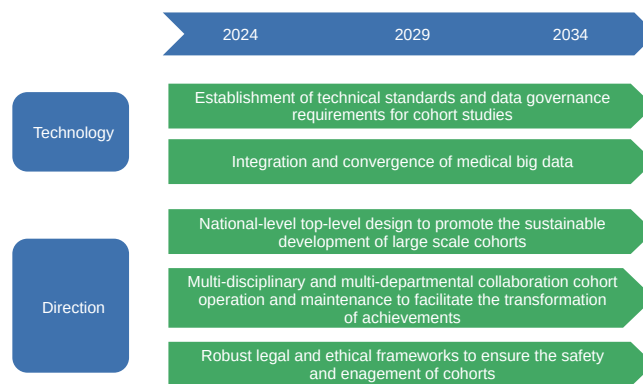


Figure 9.6 Roadmap of the engineering research front of "construction and application of big data system for cohort study"

9.1.2.3 Tissue-wide cellular atlases

Cells are the fundamental building blocks of life, forming various tissues and organs that work together to sustain normal physiological functions within the human body. Although all cells share the same genetic coding information, specific patterns of gene expression enable them to fulfill the unique physiological roles required by different tissues and organs, contributing to cellular diversity. Historically, scientists classified cells based on their morphological characteristics, tissue origin, and physiological

functions. However, the advent and advancement of single-cell sequencing have significantly enhanced our understanding of cellular complexity. By examining the transcriptomic profiles of individual cells, researchers can further categorize the same cell type into different subgroups, with differences in transcriptomes reflecting their functional variations. The identification of cell subpopulations has transformed numerous fields, including developmental biology, neuroscience, immunology, cancer research, and regenerative medicine. Investigating the biological roles of specific cell subpopulations in development, disease, and regeneration has attracted substantial interest among scientists, leading to deeper insights into disease mechanisms, developmental regulation, cell differentiation, and tissue repair. Recently, the emergence of spatial transcriptomics has provided critical information regarding the spatial distribution of cells within tissues and organs, highlighting the significance of cellular location. Understanding the spatial transcriptional landscape is essential for studying cellular interactions in their respective environments. Furthermore, the introduction of additional single-cell analytical techniques, such as single-cell proteomics and single-cell metabolomics, is poised to further enrich our comprehension of cellular dynamics.

Tissue-wide cellular atlases represent a comprehensive, high-resolution mapping of cell types, employing techniques such as single-cell and spatial omics to illustrate the diversity of cell types and their spatial distribution across all human tissues and organs, alongside their molecular characteristics. The overarching goal of the whole organization cell atlas is to thoroughly elucidate the diversity and complexity of human cells, including various aspects of human development, disease, and injury. This initiative promotes the in-depth advancement of molecular biology, genomics, and disease research, thereby establishing a robust foundation for future medical innovations. Constructing a human whole tissue cell atlas necessitates the acquisition of single-cell sequencing from a variety of tissues and organs, demanding substantial investments in labor, material resources, and financial support. Furthermore, the collection and processing of precious human samples require ongoing efforts and must adhere to ethical reviews and approvals. Therefore, the successful realization of the tissue-wide cell atlas relies heavily on extensive collaboration and adequate financial backing. To attain a more comprehensive understanding of cell states and functions, researchers have begun to integrate various omics data, including transcriptomics, proteomics, and epigenomics. This integration facilitates a deeper insight into the molecular characteristics of cells, enhancing our understanding of the mechanisms underlying human development, disease, and injury. In addition to single-cell level analyses, researchers are working to enhance the spatial resolution of cell maps. By advancing spatial transcriptomic techniques or combining these methods with imaging techniques, a more nuanced understanding of the spatial distribution and interactions of cells within tissues and organs can be achieved. As the volume of cell atlas data continues to expand, big data analysis and AI algorithms have become increasingly instrumental in data processing and mining. These technologies aid researchers in uncovering patterns and associations within vast datasets, thereby accelerating the construction and analysis of cell atlases. Nonetheless, the development of cell atlases still encounters several challenges, including data standardization, optimization of data analysis, data storage, and the definition and annotation of cell types. Moreover, the clinical application of cell atlases necessitates time for validation and transformation.

The application value of the tissue-wide cell atlas primarily lies in enhancing our understanding of tissue and organ functions, human development, disease mechanisms, treatment interventions, the human immune system, and regenerative medicine. Firstly, the tissue-wide cell atlas provides a clear representation of the cellular composition and intercellular interactions within tissue organs, illustrating cellular functions at both the molecular and cellular levels. This comprehensive understanding facilitates *in vitro* organ manufacturing and addresses the pressing issue of donor shortages in organ transplantation. Furthermore, the integration of induced pluripotent stem cells (iPSCs) to create patient-derived tissue organs holds promise for mitigating immune rejection in organ transplants. Secondly, employing the cell atlas to detail the developmental processes of tissues and organs in relation to both timelines and spatial positions significantly enhances our comprehension of human tissue and organ development. This knowledge is crucial for informing *in vitro* tissue and organ manufacturing, as it aims to replicate the natural developmental processes of human tissues and organs as closely as possible. Moreover, by creating a detailed cellular map of human diseases, particularly cancer, we can advance our understanding of disease mechanisms. For instance, identifying specific biomarkers associated with particular cancers can serve as targeted treatment options, thereby reducing the likelihood of off-target drug effects and improving treatment efficacy. Additionally, examining the complex interactions within the immune system enables scientists to reassess both common and rare diseases, especially autoimmune diseases, and develop innovative

treatment methods. The completion of the human whole tissue cell atlas is also pivotal for advancing personalized medicine. Each cell contains the organism's genome, and through gene sequence mapping, researchers can uncover the "code" associated with various diseases and phenotypes. This accelerates the understanding of disease onset and progression, thereby enhancing disease diagnosis and facilitating tailored treatment options. Furthermore, the tissue-wide cell atlas has spurred advancements in regenerative medicine. By providing a detailed comparison of specific cells across the human body, the human cell atlas reveals novel cellular functions and supplies critical information for *in vitro* tissue engineering and regenerative medicine research.

Currently, in the field of "tissue-wide cellular atlases", the top three countries with the highest number of core papers are the USA, China, and Germany (Table 9.7). Notably, China contributes 39.76% of core papers, establishing itself as a leading nation in this research area. An examination of the collaboration networks among major countries reveals strong partnerships among the top ten countries (Figure 9.7).

The leading ten institutions responsible for core papers on "tissue-wide cellular atlases" are located in the USA, China, the UK, and Sweden. The top three institutions, including Harvard University, Stanford University, and Chinese Academy of Sciences (Table 9.8), were from the USA and China. The collaboration network among major institutions illustrates robust cooperation among American research institutions, with some collaboration evident among other international entities (Figure 9.8).

The construction of a comprehensive cellular map of the entire human organism represents a global scientific initiative that

Table 9.7 Countries with the greatest output of core papers on "tissue-wide cellular atlases"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	229	45.53	34 786	151.90	2019.9
2	China	200	39.76	20 745	103.72	2009.4
3	Germany	66	13.12	10 593	160.50	2020.0
4	UK	66	13.12	9 166	138.88	2020.2
5	Switzerland	35	6.96	7 092	202.63	2019.8
6	Canada	30	5.96	5 484	182.80	2020.0
7	Sweden	28	5.57	7 061	252.18	2020.0
8	Japan	23	4.57	5 125	222.83	2019.6
9	Netherlands	22	4.37	4 404	200.18	2019.7
10	France	20	3.98	4 951	247.55	2019.7

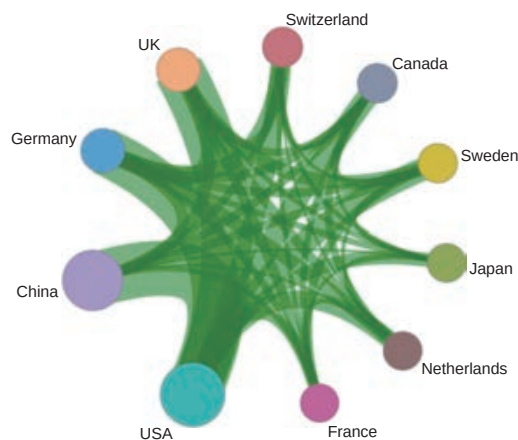


Figure 9.7 Collaboration network among major countries in the engineering research front of "tissue-wide cellular atlases"

necessitates collaborative efforts from researchers worldwide. By integrating spatial information, multi-omics data, and population analyses, a definitive version of the human cell atlas will offer invaluable resources for investigating the mechanisms of cell fate determination, significantly impacting the identification of normal and diseased cellular states within the human body (Figure 9.9).

Table 9.8 Institutions with the greatest output of core papers on “tissue-wide cellular atlases”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	53	10.54	10 471	197.57	2020.2
2	Stanford University	35	6.96	7 019	200.54	2020.0
3	Chinese Academy of Sciences	27	5.37	2 780	102.96	2020.4
4	University of California, San Francisco	25	4.97	4 570	182.80	2020.6
5	Broad Institute of MIT and Harvard	22	4.37	4 464	202.91	2020.4
6	University of Cambridge	21	4.17	3 912	186.29	2020.7
7	Massachusetts Institute of Technology	20	3.98	3 602	180.10	2020.2
8	Karolinska Institute	19	3.78	5 292	278.53	2019.8
9	University of California, San Diego	18	3.58	2 795	155.28	2020.6
10	University of Washington	17	3.38	2 940	172.94	2019.8

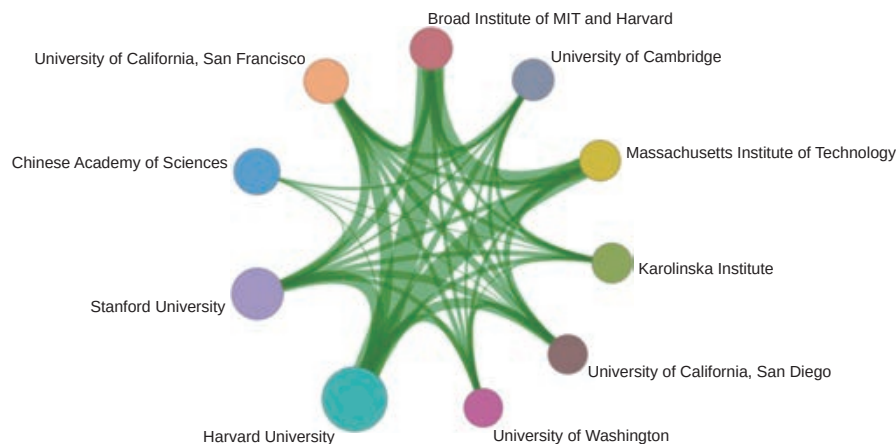


Figure 9.8 Collaboration network among major institutions in the engineering research front of “tissue-wide cellular atlases”

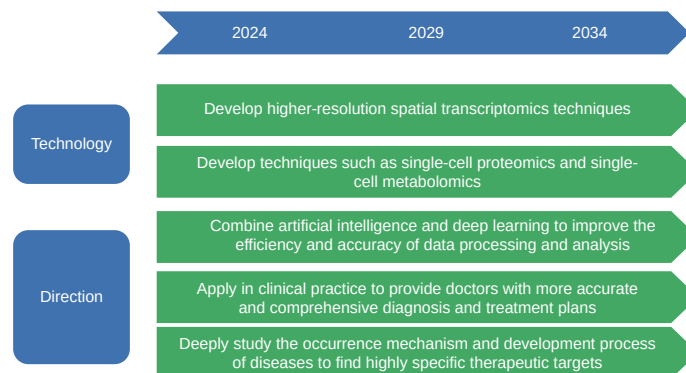


Figure 9.9 Roadmap of the engineering research front of “tissue-wide cellular atlases”

9.2 Engineering development fronts

9.2.1 Trends in the Top 10 engineering development fronts

This section of the review outlines the top ten engineering development areas in the fields of medicine and health, including basic medicine, clinical medicine, pharmacy, traditional Chinese medicine, medical informatics, and biomedical engineering (Table 9.9). The emerging areas of focus include “the gene editing technology for targeted large DNA fragment insertion”, “life spatiotemporal omics technology”, “human phenome analysis technology”, “general-duty cancer vaccines”, and “bioengineering of human organs”. Traditional research efforts have concentrated on “artificial intelligence-assisted early screening and diagnosis of cancer”, “artificial intelligence-assisted surgical navigation systems”, “organoid-on-chip in anti-cancer drug screening”, “brain-computer interface chips”, and “large language models in medical decision support”. A comprehensive list of all patents related to these ten areas, published between 2018 and 2023, can be found in Table 9.10.

Table 9.9 Top 10 engineering development fronts in medicine and health

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	The gene editing technology for targeted large DNA fragment insertion	133	201	1.51	2021.4
2	Life spatiotemporal omics technology	297	2 023	6.81	2021.7
3	Artificial intelligence-assisted early screening and diagnosis of cancer	1 087	3 753	3.45	2021.2
4	Human phenome analysis technology	1 630	3 977	2.44	2021.0
5	Artificial intelligence-assisted surgical navigation system	870	8 818	10.14	2020.8
6	General-duty cancer vaccines	261	1 094	4.19	2020.9
7	Organoid-on-chip in anti-cancer drug screening	535	1 432	2.68	2021.5
8	Bioengineering human organs	165	318	1.93	2021.0
9	Brain-computer interface chip	184	546	2.97	2020.5
10	Large language models in medical decision support	420	1 310	3.12	2022.1

Table 9.10 Annual number of core patents published for the Top 10 engineering development fronts in medicine and health

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	The gene editing technology for targeted large DNA fragment insertion	9	11	14	25	29	45
2	Life spatiotemporal omics technology	19	17	32	40	63	126
3	Artificial intelligence-assisted early screening and diagnosis of cancer	96	98	154	203	210	326
4	Human phenome analysis technology	170	201	241	295	318	405
5	Artificial intelligence-assisted surgical navigation system	120	114	104	201	160	171
6	General-duty cancer vaccines	29	34	43	45	59	51
7	Organoid-on-chip in anti-cancer drug screening	28	37	71	92	120	187
8	Bioengineering human organs	21	18	23	25	35	43
9	Brain-computer interface chip	33	26	32	28	36	29
10	Large language models in medical decision support	5	16	36	48	103	212

(1) The gene editing technology for targeted large DNA fragment insertion

The pursuit of efficient and precise targeted insertion of large DNA fragments through gene editing technology continues to pose a significant challenge for the scientific community. Since the first successful DNA insertion via homologous recombination in the 1980s, researchers have actively explored the domain of genome editing. The past decade, marked by rapid advancements in the CRISPR-Cas system, has brought substantial breakthroughs in the area of large-fragment DNA insertion. This technology demonstrates remarkable potential across various applications, including gene and cell therapy, disease modeling, and plant and animal breeding, thereby attracting extensive attention and investment. Notably, large-fragment DNA insertion has been identified as one of the seven key technologies to watch in 2024 by *Nature*.

Despite substantial progress, challenges persist in large-fragment DNA insertion technology. Foremost among these is the urgent issue of low insertion efficiency. Although CRISPR technology has substantially enhanced the editing efficiency of small DNA fragments, its efficacy for large-fragment DNA remains limited and often falls short of desired outcomes. Additionally, the length of the inserted DNA is constrained, as currently available techniques struggle to stably integrate fragments exceeding several tens of kilobases. Moreover, the precision of insertion requires improvement; existing gene editing technologies are prone to off-target effects and unwanted byproducts, which compromise the effectiveness of the edits. Furthermore, large-fragment insertion frequently necessitates synchronization with the cell cycle. The optimization of delivery systems also presents a significant challenge, as effectively delivering CRISPR editing tools and large DNA fragments to target cells or tissues is critical for achieving successful insertion.

To address these challenges, researchers are focusing on overcoming technical obstacles in several key areas. On one hand, the continuous development of novel gene editing tools presents opportunities to enhance both the efficiency and precision of large-fragment DNA insertion. On the other hand, in-depth investigations into the mechanisms underlying exogenous DNA insertion may help mitigate the limitations of current technologies. Additionally, optimizing delivery systems through physical or chemical methods is essential for improving the delivery efficiency of gene editing tools and DNA.

China boasts a robust research foundation in the field of gene editing, particularly in gene therapy, bolstered by significant policy and regulatory support that has fostered a favorable environment for research and application. The pace of clinical translation is accelerating, and the further development of this technology is expected to yield new breakthroughs and hope across various fields, including basic research, cell therapy, plant and animal breeding, and synthetic biology.

(2) Life spatiotemporal omics technology

Life spatiotemporal omics technology offers precise detection of genetic and molecular expression features within tissue cells, capturing both continuous-time and spatial dimensions. This technology facilitates a detailed analysis of the qualitative, quantitative, spatial, temporal, and directional characteristics of molecules and cells, ultimately revealing the communication networks and regulatory mechanisms underpinning complex biological processes. Following the completion of the Human Genome Project, spatiotemporal omics technology has evolved significantly, with rapid advancements in spatial analysis techniques within the multi-omics framework; however, progress in temporal dimension analysis is still in its nascent stages.

Significant breakthroughs have already been achieved in key research areas such as developmental biology, complex diseases, botany, and neuroscience. For instance, researchers have gained insights into axolotl brain regeneration mechanisms and the regulatory processes governing mouse embryonic development. Nonetheless, the development of spatiotemporal omics technology faces several critical challenges that require urgent attention: enhancing detection sensitivity and accuracy; resolving issues related to multi-omics co-analysis; addressing challenges in 3D detection techniques; applying long-read technologies effectively in the spatiotemporal context; improving *in vivo* detection capabilities; ensuring compatibility with a wider array of sample types; increasing detection throughput whereas reducing costs; advancing the application of bioinformatics analysis in managing large-scale datasets; establishing universal analytical methods for cross-omics data analysis; constructing comprehensive databases equipped with advanced analytical techniques and user-friendly interfaces; promoting the widespread use of spatiotemporal omics in clinical settings; and fostering global collaboration in significant scientific research projects across

laboratories.

China, recognized as a leading contributor to the completion of the Human Genome Project, has recently transitioned its development trajectory in spatiotemporal omics technology from initial followership to a position of synchronous progression. The country has steadily established itself as a global leader in this field, equipped with robust technological research and development capabilities, extensive scientific research applications, and mature large-scale research models. With these strengths, China is well-positioned to spearhead the comprehensive development of spatiotemporal omics technology on a global scale. This leadership will facilitate the translation of products and clinical applications in clinical testing and pathology, heralding breakthroughs and offering new hope for disease diagnosis, drug development, and precision medicine.

(3) Artificial intelligence-assisted early screening and diagnosis of cancer

As one of the major global health threats, early detection and diagnosis of cancer are crucial for improving patient survival rates and reducing treatment costs. The rapid advancement of AI technology has introduced new opportunities for early cancer screening and diagnosis. Through deep learning algorithms, AI can extract valuable information from vast amounts of medical data to identify early signs of tumors. Additionally, AI can analyze patients' medical histories, genomic data, and biomarkers to comprehensively assess individual risk, providing doctors with more accurate diagnostic support. Key technologies involved include: image recognition and analysis, where AI analyzes medical imaging data; machine learning, which allows AI to learn from large datasets and recognize patterns of cancer and certain benign lesions; natural language processing, enabling AI to process and analyze unstructured data in electronic health records to assist in evaluation, diagnosis, and management; and predictive modeling, which constructs models to predict an individual's risk of developing cancer. Currently, AI is widely used in the early screening of cancers such as thyroid, breast, lung, and colorectal cancer. By integrating with the Internet of Things and the metaverse, AI can evolve into a new form of productivity, showcasing immense potential in early cancer screening and diagnosis. However, challenges such as data privacy and security, algorithm transparency and fairness, technical accuracy, legal and ethical issues, and centralized data sharing difficulties remain. With the continued maturation of technology and the refinement of relevant laws and regulations, AI-assisted early cancer screening and diagnosis is expected to play an increasingly important role in cancer prevention and control.

(4) Human phenome analysis technology

The interaction between genetic and environmental factors plays a crucial role in shaping human traits, commonly referred to as phenotypes. The phenome includes a comprehensive set of biological, physical, and chemical characteristics that evolve over an organism's life cycle, including stages from embryonic development through birth, growth, aging, and ultimately, death. Phenotypes can be categorized into macro-phenotypes and micro-phenotypes. Macro-phenotypes include observable traits such as imaging characteristics, physical features, disease symptoms, health status, and environmental adaptability. In contrast, micro-phenotypes are concerned with cellular and molecular elements, including gene transcription, protein expression, metabolite levels, cellular immunity, and microbiota.

The field of life sciences has transitioned from the study of single genetic loci in the pre-genomic era to comprehensive whole-genome analysis in the genomic era, and is now advancing into the post-genomic era. This new era is marked by a multi-dimensional, cross-scale approach to analyzing the human phenome, which highlights the significance of human phenome analysis technologies. The International Human Phenome Project, initiated by Chinese scholars, has established the world's first cross-scale, multi-dimensional deep phenotyping platform. It has also introduced the Quartet, the first set of multi-omics reference materials, along with the inaugural deep phenotyping core cohort of a thousand individuals targeting 24 000 phenotypes across 23 categories. Additionally, it has created the world's first Human Phenome Altas.

The trend in phenome analysis technology is moving towards one-stop measurement and analysis of the human phenome. Currently, Fudan University, in collaboration with the International Human Phenome Institutes (Shanghai) in China, the Institute for Systems Biology and the Phenome Health organization in the USA, and the Weizmann Institute of Science in Israel, has established integrated platforms for phenome measurement and big data analysis. These collaborative efforts are fostering the

development of multimodal AI models that leverage extensive phenome big data. Achieving high-throughput, deep-coverage detection and correlation analysis of various dimensions of the phenome within a unified framework is essential for advancing Human Phenome Analysis Technology. Additionally, highly sensitive and non-invasive molecular imaging techniques can provide visual and quantitative insights into spatial coverage and molecular processes. Spatial omics, which combines molecular biology, histology, and imaging technologies, enhances the spatial resolution capabilities essential for phenome research. Therefore, the continued development of molecular imaging and spatial omics will be vital for future advancements. Moreover, addressing the current gaps in multi-dimensional phenome association analyses, establishing an international standardization system for human phenome analysis, and developing multi-scale, multimodal AI models will significantly deepen our understanding of health and disease mechanisms, ultimately propelling new productivity advances in China's biomedical sector.

(5) Artificial intelligence-assisted surgical navigation system

The AI-assisted surgical navigation system is an intraoperative positioning technology developed utilizing three-dimensional image reconstruction. This innovative system aligns actual intraoperative findings with preoperative images, enabling surgeons to more accurately identify the location, extent, and association of lesions with surrounding tissue during procedures. By facilitating the complete removal of the lesion whereas safeguarding vital structures and functional areas, the system enhances surgical safety. Consequently, this technology not only improves operational accuracy and reduces complications but also shortens postoperative recovery times, ultimately enhancing both the safety and efficacy of surgical interventions. As science and technology continue to advance, AI-assisted surgical navigation systems are rapidly evolving, presenting broad prospects for future application. Surgical navigation technology was first integrated into neurosurgery by Roberts et al. in 1986, and its clinical value in that field has since become increasingly recognized, rendering it an essential tool for surgical practices. Today, these systems find widespread use in various medical specialties, including otolaryngology, head and neck surgery, spinal surgery, and stomatology. A market research report published by Global Information in June 2023 forecasts that the global demand for neuro-navigation systems will grow from 4.33 billion dollars in 2022 to nearly 10.14 billion dollars by 2030, representing a compound annual growth rate of 10.0% during that period. According to the 2021 domestic health statistics report, there are 1 651 tertiary hospitals in the country, which comprise only 4.5% of the total number of hospitals. Currently, only a handful of these hospitals are equipped with surgical navigation technology, highlighting a significant gap between the strong clinical demand for navigation systems and their limited penetration in healthcare. The primary barriers to adoption include high costs, insufficient intelligence features, and a plethora of supporting components, complex operational requirements, and substantial space demands. Initially, the surgical navigation system was developed primarily in North America and Europe, with companies like Brainlab, Medtronic, and Stryker leading the market. Most core technologies remain monopolized by foreign medical firms. Although China's neuronavigation technology has advanced rapidly in recent years, much of this progress relies on the assembly and OEM of foreign technologies and modules. Thus, there is a pressing need to develop an AI-assisted surgical navigation system that is intelligent, cost-effective, accurate, and intuitive, which holds considerable social and economic value. The overarching research and development strategy for navigation technology should focus on "subtraction of hardware and addition of performance". On one hand, the system's hardware structure can be streamlined through device optimization and configuration refinement. On the other hand, by leveraging big data and AI, enhancements in computational efficiency and reductions in system errors can be achieved through innovative algorithms and improved functional integration, thereby boosting overall system performance. Furthermore, the integration of AI with AR/VR technologies can offer surgeons real-time three-dimensional visual navigation, enriching their spatial perception capabilities. Additionally, when combined with surgical robotic systems, AI can facilitate more precise operations through real-time data feedback, significantly minimizing operational errors. Looking ahead, AI-assisted surgical navigation systems are positioned to reduce surgical trauma, decrease recovery times, and lower the risk of complications through more accurate positioning and navigation. This advancement will enable surgeons to conduct complex procedures with smaller incisions, thereby reducing patient injury. The combination of AI and advanced imaging technologies may also foster the emergence of non-invasive surgical interventions, employing micro-robots or nanotechnology for *in vivo* diagnostics and treatment, further mitigating tissue damage. In summary, AI-assisted surgical navigation systems are evolving from traditional image-guided approaches to intelligent, personalized, and fully automated surgical methodologies. With ongoing technological progress, these systems are expected to

significantly enhance the safety, efficiency, and accuracy of surgical practices, thereby transforming the medical service landscape. Nevertheless, addressing challenges related to data quality, multimodal data integration, real-time system functionality, stability, security, and the collaboration between healthcare professionals and AI engineers, as well as ethical and accountability considerations, will be crucial. These innovations will propel the surgical field toward high precision and full automation.

(6) General-duty cancer vaccines

General-duty cancer vaccines are designed to activate the body's immune system to recognize and attack multiple cancer types rather than targeting a single type. This innovative approach aims to develop a more universal and broadly applicable cancer treatment. Central to the effectiveness of such vaccines is the identification of shared cancer antigens that are present across various cancer types. These antigens can be incorporated into vaccine formulations in the form of peptides, proteins, or nucleic acids (DNA/RNA). Furthermore, adjuvants play a crucial role in enhancing the effectiveness of these vaccines by boosting the body's immune response to common cancer antigens, thereby improving the targeting and destruction of cancer cells. General-duty cancer vaccines have the potential to treat a wide range of cancers, inhibiting tumor growth, reducing metastasis, preventing recurrence, improving quality of life, and extending survival rates. As the global incidence of malignant tumors continues to rise, countries such as China, along with developed nations in Europe and the USA, are increasingly investing in cancer vaccine research. However, current cancer vaccines are primarily developed for specific cancer types and lack a universal design, with no general-duty cancer vaccine available on the market today. The discovery of shared cancer antigens and the development of advanced adjuvants are pivotal to advancing general-duty cancer vaccine technology. The integration of this technology with clinical big data, AI, immunology, and materials science holds promise for providing new hope for the recovery of many cancer patients.

(7) Organoid-on-chip in anti-cancer drug screening

Organ-on-chip (OOC), also known as organoid chip, is a microphysiological system (MPS) that integrates organoid technology with microfluidic chip or microplate technologies. Cancer-on-chip (COC) represents an innovative experimental model that involves seeding patient-derived organoids (PDO) into microfluidic devices or microplates, effectively simulating three-dimensional tumor structures and their surrounding microenvironments. COC can replicate the phenotypic and biological characteristics of cancers at the organ level, thus serving as a platform for anti-cancer drug screening. Key technologies essential for the establishment of COC include the *in vitro* construction of PDOs, the plating of PDO suspensions into microfluidic chips or microplates, and the cultivation of COC in a 37 °C incubator. Additionally, continuous medium perfusion is implemented to ensure adequate exchange of nutrients and oxygen, whereas anti-cancer drugs are administered to evaluate their cytotoxic effects on organoids. The detection indicators for organoids include various morphological and biochemical parameters. Currently, PDOs and OOCs are extensively utilized in drug toxicity evaluation, drug sensitivity analysis, and efficacy screening of novel compounds. This innovative technology has fundamentally transformed traditional drug development processes, significantly reducing the reliance on experimental animals. As COC can accurately recapitulate the pathophysiological characteristics of original diseases, it is increasingly regarded as a viable alternative for personalized medicine in cancer patients. Governments, including those of China and other developed nations, have ramped up investments in this field. Several high-tech enterprises dedicated to the biofabrication of OOC systems have begun to establish a substantial presence. Looking ahead, COC is expected to evolve from a single-cell type model to a co-culture system that incorporates a cancer microenvironment, including cancer-associated fibroblasts, vascular cells, and immune cells. Moreover, the development of advanced devices such as multi-organ and multi-tissue combined chips (integrating PDOs with organs like the heart, liver, and kidney) will facilitate simultaneous screening of drug efficacy as well as the assessment of cytotoxicity and side effects. Therefore, COC holds significant promise for advancements in drug screening, toxicity testing, disease modeling, and personalized medicine.

(8) Bioengineering human organs

Bioengineered human organs leverage advanced technologies from engineering, biology, and regenerative medicine to construct or repair tissues and organs. This process involves the combination of stem cells, biomaterials, bioactive factors, and controlled

physical-chemical conditions. The primary objectives include repairing, replacing, or enhancing bodily functions, addressing the shortage of organ donors for transplantation, and developing new strategies and technologies for disease research and drug screening. Key technical challenges in the development of bioengineered organs include:

- 1) Selection and expansion of seed cells: The foundation of bioengineered organs lies in the quality and quantity of seed cells. These cells are crucial for determining the success rate and functionality of organ construction.
- 2) Design and fabrication of matrix materials: The matrix materials employed must possess excellent biocompatibility and mechanical strength to support robust cell growth and facilitate effective tissue formation.
- 3) Assembly of cells and matrix materials: Creating complex organ structures and functions requires careful assembly of cells and matrix materials at both macro and microscopic levels.
- 4) Simulation and regulation of tissue microenvironment: Utilizing complex physical-chemical signals is essential for guiding cellular behavior and maintaining functionality within the engineered tissue environment.

Bioengineered organs exhibit significant potential across various fields of biomedicine. They provide essential technologies for organ repair and regenerative medicine, along with innovative tools and models for disease investigation and drug screening. Researchers are actively exploring the construction and transplantation of more complex functional organs, such as the liver, kidneys, and heart.

The field is advancing rapidly, with bioengineered organs moving from experimental research to practical applications. Both China and Western nations are placing considerable emphasis on and investing actively in the commercialization of organ engineering products. With swift developments in biology, engineering, and manufacturing technologies (organoids, organs on chips, biomaterials, 3D printing), the construction of complex human organs is becoming increasingly biomimetic and controllable. This progress is anticipated to advance regenerative medicine and the broader field of biomedicine in the future.

(9) Brain-computer interface chip

Brain-computer interface (BCI) represents an innovative communication and control technology that establishes a connection between the human or animal brain and computers or other electronic devices, bypassing traditional pathways of brain information output. As the pinnacle of human-computer interaction, the primary function of the BCI chip includes the acquisition, amplification, filtering, analog-to-digital conversion, and various other processing of EEG signals. These signals are transformed into formats recognizable by computers, followed by preprocessing and feature signal extraction, culminating in pattern recognition. Ultimately, this process converts the signals into specific commands that enable control over external devices. BCIs can be categorized into two main types: invasive and non-invasive. Invasive BCIs primarily focus on data readout, feature extraction, brain simulation, and wireless transmission. In contrast, non-invasive BCIs primarily concentrate on data readout and feature extraction. In recent years, leading commercial and academic institutions, including Neuralink in the USA, IMEC in Belgium, EPFL in Switzerland, Tsinghua University, and Tianjin University, have made significant advances and breakthroughs in the field of BCI chips. These advancements have propelled the commercial application of BCI technology in areas such as brain activity monitoring, epilepsy treatment, rehabilitation for paralyzed patients, and brain-controlled typing. Looking ahead, as chip design, neuroscience, computer science, and AI continue to evolve, the capabilities of BCI chips will expand. We can anticipate the development of more miniaturized, intelligent, highly integrated, low-power, energy-efficient, and computationally capable chips. These advancements will enhance the accuracy of brain signal reading and decoding, thereby improving control precision, response speed, and overall device intelligence, leading to a more convenient, intelligent, and efficient lifestyle for humanity.

(10) Large language models in medical decision support

Large language models (LLMs) are sophisticated AI systems designed to understand, generate, and interpret complex human languages. These models are trained on extensive amounts of textual data, enabling them to perform a variety of language-based tasks with accuracy and fluency. Key technical challenges include ensuring data quality and scale, optimizing model architecture and training, enhancing model comprehension and generation capabilities, improving interpretability and transparency, aligning

models with human feedback, and integrating multimodal data. As research on LLMs in the medical field progresses, their application in medical decision support is expected to increase. In clinical diagnosis, LLMs can analyze symptoms and medical history described by patients to provide diagnostic suggestions that aid clinicians in making preliminary judgments. By leveraging image recognition technology, LLMs can also analyze CT, MRI, and pathology images to assist in disease diagnosis. Furthermore, through the use of multimodal technology (text, imaging, and laboratory reports), LLMs can enhance the accuracy of clinical diagnoses. They can recommend personalized treatment plans based on individual patient factors, such as genetic data, medical history, and lifestyle, whereas adhering to evidence-based medicine principles to optimize treatment results. Additionally, LLMs can analyze the medications currently prescribed to patients to identify potential drug interactions and mitigate adverse reactions. LLMs also play a critical role in health monitoring and prevention. By integrating data from wearable devices, they can monitor patients' health status in real time and provide timely alerts and health advice. Utilizing big data analysis, LLMs can predict potential future health risks and suggest preventive measures. Due to their promising potential in medical decision support, both China and developed countries in Europe and the USA have prioritized research and investment in LLM technology. Applications of LLMs in clinical diagnostic support, treatment recommendations, health monitoring and prevention, and medical robotics are already emerging, with the market continuing to grow rapidly. Key breakthroughs in LLMs for medical decision support will depend on large-scale multimodal data integration, efficient pre-training and fine-tuning techniques, and models characterized by interpretability and transparency. The deep integration of LLMs with medical imaging analysis, genomics, big data analysis, robotics, and other fields is poised to bring revolutionary changes to the healthcare landscape.

9.2.2 Interpretations for three key engineering development fronts

9.2.2.1 The gene editing technology for targeted large DNA fragment insertion

Large DNA Fragment Insertion refers to the precise incorporation of relatively long DNA sequences (>1 kb or >200 bp) at specific loci within the genome using gene editing technologies. These inserted DNA sequences can carry various types of information, including, but not limited to, functional genes and regulatory elements. Although significant progress has been made in precise editing technologies targeting single or tens of base pairs, these advancements still address only a fraction of the existing needs. Large-scale genomic insertions are crucial in fields such as functional gene research, gene therapy for non-hotspot mutations and sequence deletions, disease model construction, and plant and animal breeding. The capability for large DNA fragment insertion not only fosters in-depth exploration in basic science but also opens new avenues for practical applications, potentially leading to widespread technological advancements and societal benefits in the future.

The development of targeted genomic large DNA fragment insertion technology began with the homologous recombination technique in 1980, which served as a tool for creating genetically modified animals, although it was highly inefficient. In 2013, CRISPR technology was successfully applied to mammalian cells, enabling large fragment insertions in certain cell lines. In recent years, CRISPR-derived technologies and integrase systems have made significant strides in enhancing insertion efficiency and accuracy. For instance, YIN Hao's team developed GRAND editing, an efficient and precise DNA insertion tool based on the PE system that does not require the cell cycle or exogenous DNA, achieving DNA insertions ranging from 200 bp to 1 kb. Gootenberg's and David Liu's teams combined the PE system with integrase, developing the PASTE gene editing tool that enabled insertions of up to 36 kb. In rice and maize, GAO Caixia's team developed the PrimeRoot system, achieving precise insertions as long as 11.1 kb. The widespread application of large DNA fragment insertion drives advancements in gene therapy and synthetic biology.

However, current methods face several limitations. Firstly, achieving insertions of sizes ranging from 100 kb to Mb remains challenging, which restricts certain applications. Secondly, current methods often leave scars in the insertion products, complicating the achievement of scarless insertions. Thirdly, the versatility of large-fragment insertion systems is a notable concern. The mechanisms of large-fragment insertion and the enzymes used are typically complex, and overly replicated systems can lead to inefficiencies at numerous endogenous sites, meaning the reported data may not fully represent the potential outcomes. Lastly, the limitations of delivery vectors and methods significantly affect the efficiency and length of large-fragment

insertions in non-model cells or organisms.

Addressing these challenges will necessitate a focus on the following areas: ① exploring new methodologies for inserting sequences within the 100 kb to Mb range; ② developing innovative approaches for scarless insertions; ③ elucidating the endogenous molecular mechanisms that currently limit the efficiency of enzymes used for large-fragment DNA insertion; ④ optimizing existing delivery methods whereas exploring new delivery strategies.

Between 2018 and 2023, a total of 133 core patents have been published in the emerging field of “the gene editing technology for targeted large DNA fragment insertion”. The leading patent holders are from China, the USA, and the UK (Table 9.11). Notably, 68.42% of these patents have been filed by Chinese applicants, positioning China as a frontrunner in this domain. There exist collaborative associations between the USA and both China and the UK (Figure 9.10). The primary institutions holding these core patents include Hubei University, Southern Medical University, Blood Diseases Hospital of the Chinese Academy of Medical Sciences, and Tianjin University of Science & Technology (Table 9.12); however, collaboration among the major institutions is currently lacking.

The future development of targeted large DNA fragment insertion technology can be categorized into four main directions. ① Advancement of the technology itself: This includes the creation of more efficient tools capable of inserting larger fragments, featuring site versatility, and enabling scarless insertions. ② Progress in associated technologies: This includes improvements in *in vivo* and *in vitro* delivery methods, as well as donor preparation technologies for large DNA fragments. ③ Expansion of medical applications: Gene editing involving large DNA fragments has the potential to address thousands of genetic diseases through gene and cell therapy, although current technological limitations constrain the range of applications. ④ Broad prospects in synthetic biology and agriculture: The potential applications in these fields are particularly promising.

As research into gene editing technology for large DNA fragment insertion advances, a number of cutting-edge technologies are anticipated to emerge. These technologies include *in situ* nucleic acid synthesis, scarless and cut-free DNA insertion methods, multiplex and combinatorial editing tools, the discovery and directed evolution of new CRISPR-Cas systems, as well as novel vectors and delivery systems.

In the next 5 to 10 years, the application scenarios for targeted large DNA fragment insertion technology are anticipated to expand significantly, primarily in the following key areas: gene and cell therapy, synthetic biology and gene circuit design, agriculture and animal breeding, and personalized medicine and precision medicine. These scenarios highlight the substantial potential of targeted large DNA fragment insertion technology in facilitating breakthroughs and transformations across medicine, agriculture, industry, and basic research, signaling major advancements on the horizon (Figure 9.11).

Table 9.11 Countries with the greatest output of core patents on “the gene editing technology for targeted large DNA fragment insertion”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	China	91	68.42	132	65.67	1.45
2	USA	34	25.56	62	30.85	1.82
3	UK	3	2.26	11	5.47	3.67
4	Spain	2	1.50	2	1.00	1.00
5	Japan	2	1.50	2	1.00	1.00
6	Netherlands	1	0.75	1	0.50	1.00
7	Canada	1	0.75	0	0.00	0.00
8	Hungary	1	0.75	0	0.00	0.00

Note: Choose a publication date from January 1st, 2018 to December 31st, 2023, the same below.

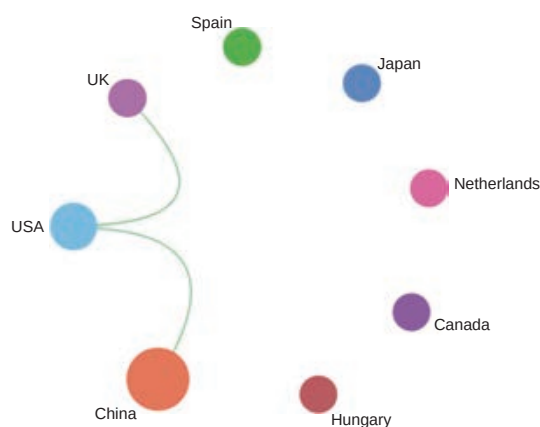


Figure 9.10 Collaboration network among major countries in the engineering development front of “the gene editing technology for targeted large DNA fragment insertion”

Table 9.12 Institutions with the greatest output of core patents on “the gene editing technology for targeted large DNA fragment insertion”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Hubei University	3	2.26	14	6.97	4.67
2	Southern Medical University	3	2.26	9	4.48	3.00
3	Blood Diseases Hospital, Chinese Academy of Medical Sciences	3	2.26	6	2.99	2.00
4	Tianjin University of Science & Technology	3	2.26	3	1.49	1.00
5	Harvard University	2	1.50	22	10.95	11.00
6	Sun Yat-sen University	2	1.50	18	8.96	9.00
7	East China University of Science and Technology	2	1.50	6	2.99	3.00
8	Beijing Institute of Technology	2	1.50	5	2.49	2.50
9	Inscripta, Inc.	2	1.50	4	1.99	2.00
10	China Pharmaceutical University	2	1.50	2	1.00	1.00

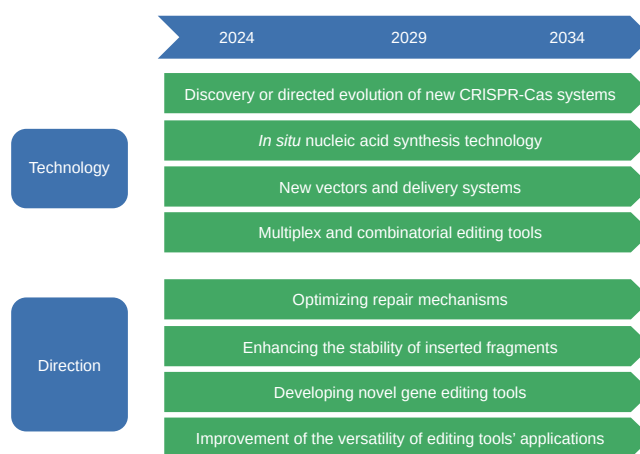


Figure 9.11 Roadmap of the engineering development front of “the gene editing technology for targeted large DNA fragment insertion”

9.2.2.2 Life spatiotemporal omics technology

Spatiotemporal omics technology provides a comprehensive analysis of the genetic and molecular expression features of biological tissues and organs across both temporal and spatial dimensions. This approach includes various omics levels, including the genome, epigenome, transcriptome, and proteome. Unlike traditional sequencing or detection technologies, spatiotemporal omics enables simultaneous detection in continuous time and spatial dimensions, offering a novel analytical perspective that fosters new discoveries and breakthroughs. With high precision, this technology allows for subcellular and single-cell level analyses whereas maintaining a broad field of view for examining large tissue sections. Its versatility makes it suitable for different tissue types and states.

Consequently, spatiotemporal omics technology has made significant contributions to major research fields, including developmental biology, complex diseases, botany, and neuroscience. Since the emergence of human genome technology, imaging-based spatiotemporal omics has rapidly progressed into two primary technical approaches: *in situ* sequencing technology and *in situ* hybridization technology. In 2016, the Karolinska Institute in Sweden introduced spatial transcriptomics technology, marking a significant milestone in sequencing-based spatiotemporal omics. This innovation showed considerable technological promise and application potential. In 2020, spatial transcriptomics was recognized as the “Technology of the Year” by *Nature Methods* journal, and in 2022, it was cited as one of the seven “disruptive” technologies worthy of attention by *Nature*.

In May 2022, Stereo-seq, the world’s first subcellular-resolution, centimeter-scale field of view spatial transcriptomics technology, developed entirely by Chinese scientists, was revealed globally in *Cell*. Since then, China has achieved breakthroughs in spatiotemporal omics technology, transitioning from a position of catch-up to one of leadership and innovation. This shift has contributed to the establishment of guidelines and directions for the development of spatiotemporal life science technology on a global scale, significantly accelerating its application across major scientific research domains and clinical settings.

Important issues to address in the field of spatiotemporal omics technology include enhancing detection sensitivity and accuracy, further tackling challenges related to dispersion and low capture efficiency during genetic molecule capture, and improving spatial segmentation accuracy to achieve single-cell and subcellular resolution for precise biological feature analysis at the spatial single-cell scale. Additional areas that require resolution include multi-omics co-analysis, which includes simultaneous analysis across both temporal and spatial dimensions, as well as concurrent sequencing of the genome, epigenome, transcriptome, and proteome. Furthermore, there is a need to address the challenges posed by three-dimensional detection technology, overcome the limitations of long-read technology within the context of spatiotemporal omics, and tackle the difficulties associated with *in vivo* detection applications.

It is also essential to ensure compatibility with various sample types, including fresh frozen samples, paraffin-embedded samples, and samples fixed through diverse methods. The field must address the need for higher detection throughput, reduced detection costs, and widespread applicability, whereas enabling efficient bioinformatics analysis for large-scale data. Additionally, efforts should focus on developing universal analysis methods for cross-omics data, constructing comprehensive databases featuring advanced analytical techniques and user-friendly interfaces, promoting extensive clinical applications, and facilitating global collaboration among laboratories engaged in significant scientific research projects.

Branches of the spatiotemporal omics technology field that critically impact practical applications include: Advancing the overall performance of underlying detection technologies, building efficient and standardized bioinformatics analysis methods, platforms, and databases for spatiotemporal omics big data. Optimizing application scenarios in various research fields, especially in clinical diagnosis and pathology testing. Promoting international large-scale scientific research initiatives, and fostering the development of top-notch talent in the field.

Between 2018 and 2023, a total of 297 core patents have been published in the emerging field of “life spatiotemporal omics technology”. The leading patent holders are China, the USA, and Germany (Table 9.13), with Chinese applicants accounting

for 52.19% of these patents, positioning China as a frontrunner in this domain. Collaborative associations exist among the USA, Germany, and Sweden (Figure 9.12). Major core patent-owning institutions include 10x Genomics, Inc., Prognosis Biosciences, Inc., and Massachusetts Institute of Technology (Table 9.14). Additionally, a collaborative network has been established involving Broad Institute of MIT and Harvard, the Massachusetts Institute of Technology, and Massachusetts General Hospital (Figure 9.13).

So far, spatiotemporal omics technology has been extensively applied across various significant fields, including developmental biology, complex diseases, neuroscience, and plant biology. By integrating spatial location with expression profiling, spatiotemporal omics can more effectively differentiate cell types and subtypes that exhibit similar expression profiles but occupy different spatial locations and fulfill different functions. This technology enables the comprehensive construction of spatiotemporal dynamic maps of organ development at the single-cell resolution, allowing researchers to trace the developmental trajectories of cells over time.

Spatiotemporal omics accurately detects relative spatial positions and microenvironmental characteristics among cells, facilitating investigations into how the microenvironment influences diseases. The incorporation of spatial information allows for precise molecular subtyping of diseases, which may reveal new potential targets for precision therapy. Furthermore, the accurate localization of neurons enables the integration of transcriptomic subtypes with neuronal projections, providing deeper insights into the functional mechanisms of neural circuits.

In the domain of neurological diseases, spatial omics technology has been instrumental in uncovering the complex mechanisms underlying various conditions, paving the way for more comprehensive treatment strategies in the future. By addressing the challenges posed by cell wall interference through histological sectioning, spatiotemporal omics also promises significant advancements in plant biology research at both the spatiotemporal dimension and single-cell level.

To further address major life questions, future development directions in cutting-edge spatiotemporal omics technologies include spatial multi-omics co-detection, 3D omics, temporal resolution technology, and *in vivo* 3D detection. Key areas of exploration comprise: investigating the spatiotemporal regulations of multi-organ development in model organisms and non-human primates, constructing human brain maps and three-dimensional models of neural connections, studying the evolutionary patterns across various species and organs, exploring the mechanisms of skin follicle regeneration post-injury, unraveling the spatiotemporal mechanisms underlying complex diseases such as cancer, and developing application strategies for spatiotemporal omics technology in clinical pathology (Figure 9.14).

Table 9.13 Countries with the greatest output of core patents on “life spatiotemporal omics technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	China	155	52.19	331	16.36	2.14
2	USA	91	30.64	1 632	80.67	17.93
3	Germany	22	7.41	25	1.24	1.14
4	Russia	8	2.69	0	0.00	0.00
5	Republic of Korea	7	2.36	4	0.20	0.57
6	Singapore	3	1.01	5	0.25	1.67
7	UK	3	1.01	0	0.00	0.00
8	Sweden	2	0.67	253	12.51	126.50
9	France	2	0.67	13	0.64	6.50
10	Netherlands	2	0.67	13	0.64	6.50

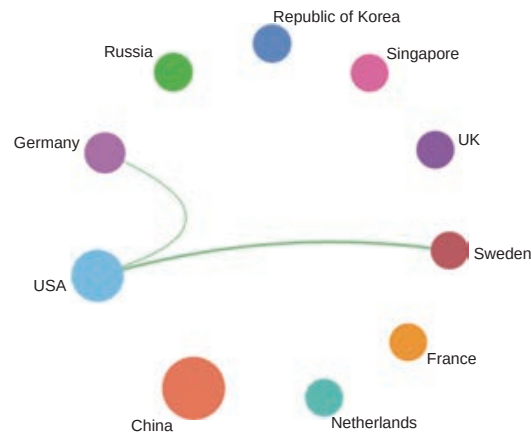


Figure 9.12 Collaboration network among major countries in the engineering development front of "life spatiotemporal omics technology"

Table 9.14 Institutions with the greatest output of core patents on "life spatiotemporal omics technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	10x Genomics, Inc.	15	5.05	660	32.62	44.00
2	Prognosys Biosciences, Inc.	12	4.04	558	27.58	46.50
3	Massachusetts Institute of Technology	8	2.69	87	4.30	10.88
4	Southeast University	8	2.69	37	1.83	4.62
5	Broad Institute of MIT and Harvard	8	2.69	19	0.94	2.38
6	Stanford University	6	2.02	4	0.20	0.67
7	Massachusetts General Hospital	5	1.68	16	0.79	3.20
8	Sick AG	5	1.68	10	0.49	2.00
9	Shanghai Jiao Tong University	5	1.68	8	0.40	1.60
10	Applied Materials, Inc.	5	1.68	5	0.25	1.00

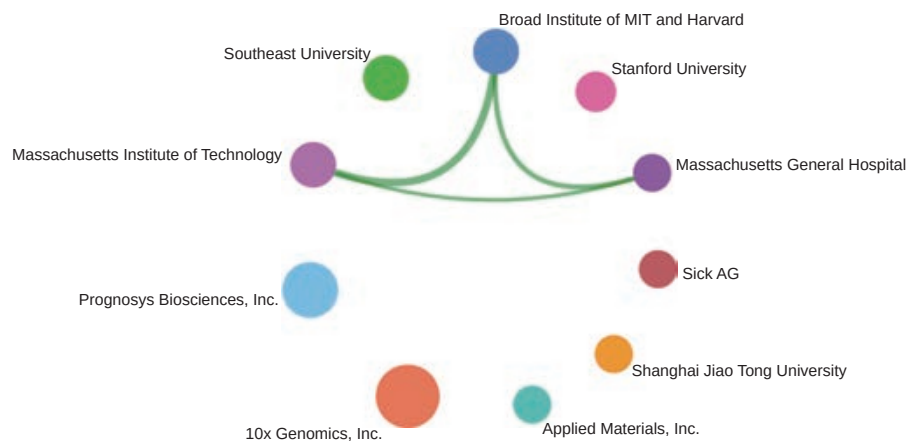


Figure 9.13 Collaboration network among institutions in the engineering development front of "life spatiotemporal omics technology"

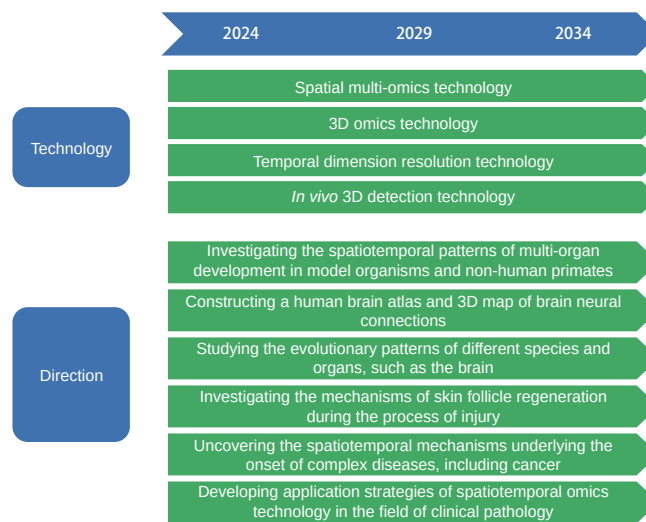


Figure 9.14 Roadmap of the engineering development front of "life spatiotemporal omics technology"

9.2.2.3 Artificial intelligence-assisted early screening and diagnosis of cancer

The development of "artificial intelligence-assisted early screening and diagnosis of cancer" can be traced back to the 1980s, initially focusing on simple computer aided diagnosis (CAD) systems that primarily relied on rule-based methods. However, these systems showed limited performance in tumor screening. In the 1990s, with the advancement of statistical and machine learning methods, AI began to be applied to tumor data analysis. Researchers achieved some success using simple algorithms for image recognition and predictive model construction. After 2010, breakthroughs in deep learning technology propelled advancements in computer vision, enabling the application of AI in medical image analysis. Multiple studies demonstrated that deep learning models surpassed human experts in identifying tumors in CT, MRI, and X-ray images. Subsequently, more AI tools underwent clinical validation and received FDA or CE certification, beginning to be applied in practical healthcare settings. AI-assisted image analysis tools have been widely adopted in tumor screening, enhancing diagnostic efficiency and accuracy.

In recent years, researchers have started applying AI to integrate multiple data sources (such as imaging, genomic, and clinical data) to achieve more comprehensive early screening and personalized risk assessment. The main research directions for AI-assisted early cancer screening and diagnosis include the following aspects: ① Image analysis: utilizing deep learning technology to improve the accuracy of automatic detection and classification of tumors in medical images like CT, MRI, and X-rays. ② Biomarker identification: developing AI algorithms to analyze genomic and blood sample data, identifying tumor-related biomarkers to aid early diagnosis. ③ Multimodal Data Integration: combining imaging, genomic, clinical data, and patient history to construct comprehensive risk assessment models, enhancing personalized screening effectiveness. ④ Natural language processing: applying NLP technology to analyze electronic health records and physician reports, extracting key information to support clinical decision-making. ⑤ Real-time monitoring and alerts: researching AI-based real-time monitoring systems to detect disease progression and recurrence risks promptly, enabling early intervention. ⑥ Interpretability and ethics: focusing on the interpretability of AI models to ensure transparency in clinical applications, and studying related ethical and privacy issues. ⑦ Systematic digital healthcare: simplifying complex problems, digitizing simple problems, programmatically addressing digital problems, and systematizing programmatic problems to facilitate the comprehensive improvement of healthcare quality through consensus guidelines and widespread coverage at the primary care level.

The research direction of "artificial intelligence-assisted early screening and diagnosis of cancer" has become a focal point in the medical field in recent years, with several successful clinical applications. For instance, the PANDA (pancreatic cancer

detection with AI) model, developed by Alibaba DAMO Academy in collaboration with multiple medical institutions, employs a “non-contrast CT + AI” approach to enable large-scale early screening of pancreatic cancer. A research team from Imperial College London’s Department of Hematology and the University of Cambridge has developed an AI model capable of identifying 13 different types of cancer from non-cancerous tissues by analyzing DNA methylation patterns, achieving an accuracy rate of 98.3%. The PNapp 5A, developed by the China Lung Cancer Prevention and Treatment Alliance, exemplifies systematic digital healthcare. It initially integrates consensus guidelines to “simplify complex problems”, further digitizes “simple problems” through AI, programmatically addresses “digital problems” via an App, and ultimately systematizes “programmatic problems” through the internet of things (IoT).

Between 2018 and 2023, 1 087 core patents have been published in the frontier field of “artificial intelligence-assisted early screening and diagnosis of cancer”, and the top three patent owners are China, the USA, and India (Table 9.15). Up to 59.71% of such patents are filed by Chinese applicants, making China one of the frontrunners in this field. The USA has cooperative relationships with multiple countries, including Australia, India, and China (Figure 9.15). The top core patent-owning institutions include Illumina, Inc., Blood Diseases Hospital of the Chinese Academy of Medical Sciences, and Fudan University (Table 9.16); Nanjing Shihe Medical Equipment Co., Ltd. has cooperative relationships with Blood Diseases Hospital of the Chinese Academy of Medical Sciences, and Fudan University (Figure 9.16).

Currently, AI has undergone multiple clinical validations, with various commercial products and research platforms being launched, driving the intelligent development of cancer screening. Despite challenges such as data privacy and ethics, the application prospects of AI in early cancer screening and diagnosis remain promising. Future key development directions and trends for artificial intelligence-assisted early screening and diagnosis of cancer include: ① further optimization of deep learning technologies; ② integration of multimodal data from imaging, genomics, clinical, and lifestyle sources to develop comprehensive personalized assessment and diagnostic tools; ③ real-time monitoring and alert systems to detect anomalies and issue warnings promptly; ④ interpretable AI to enhance clinical trust; ⑤ virtual assistants and intelligent decision support to aid physicians in diagnosis and treatment plan selection; ⑥ expanding application scenarios to improve primary healthcare coverage and quality; ⑦ empowering healthcare and wellness through metaverse medicine; ⑧ decentralized data sharing to pave the way for one-stop “healthcare and wellness”; ⑨ creating a new medical productivity model composed of AI, IoT medicine, and metaverse medicine (including GPT), aligning with new development concepts of advanced productivity; ⑩ establishing comprehensive ethical and regulatory frameworks to ensure patient data privacy and security. These development directions will drive the application of AI in early cancer screening and diagnosis, enhancing the quality and efficiency of healthcare services (Figure 9.17).

Table 9.15 Countries with the greatest output of core patents on “artificial intelligence-assisted early screening and diagnosis of cancer”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	649	59.71	1 749	46.60	2.69
2	USA	242	22.26	1 647	43.88	6.81
3	India	62	5.70	2	0.05	0.03
4	Republic of Korea	54	4.97	55	1.47	1.02
5	Australia	15	1.38	40	1.07	2.67
6	UK	14	1.29	63	1.68	4.50
7	Canada	11	1.01	62	1.65	5.64
8	Japan	10	0.92	18	0.48	1.80
9	Germany	8	0.74	33	0.88	4.12
10	Israel	6	0.55	7	0.19	1.17

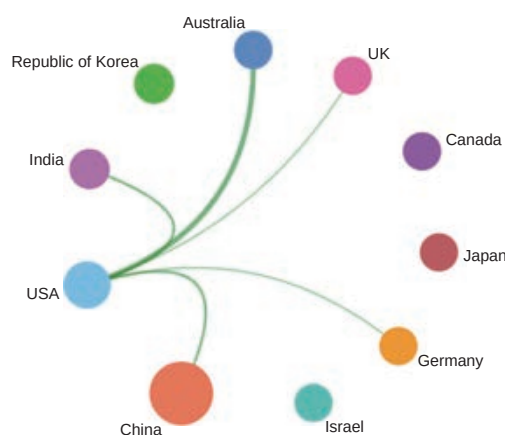


Figure 9.15 Collaboration network among major countries in the engineering development front of “artificial intelligence-assisted early screening and diagnosis of cancer”

Table 9.16 Institutions with the greatest output of core patents on “artificial intelligence-assisted early screening and diagnosis of cancer”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Illumina, Inc.	32	2.94	332	8.85	10.38
2	Blood Diseases Hospital, Chinese Academy of Medical Sciences	26	2.39	91	2.42	3.50
3	Fudan University	19	1.75	30	0.80	1.58
4	Nanjing Shihe Medical Equipment Co., Ltd.	18	1.66	41	1.09	2.28
5	Zhejiang University	18	1.66	38	1.01	2.11
6	Sun Yat-sen University	17	1.56	69	1.84	4.06
7	Guardant Health, Inc.	15	1.38	183	4.88	12.20
8	Y. Shen Bioinfo Co., Ltd.	14	1.29	10	0.27	0.71
9	F. Hoffmann-La Roche Ltd.	13	1.20	18	0.48	1.38
10	Southern Medical University	11	1.01	22	0.59	2.00

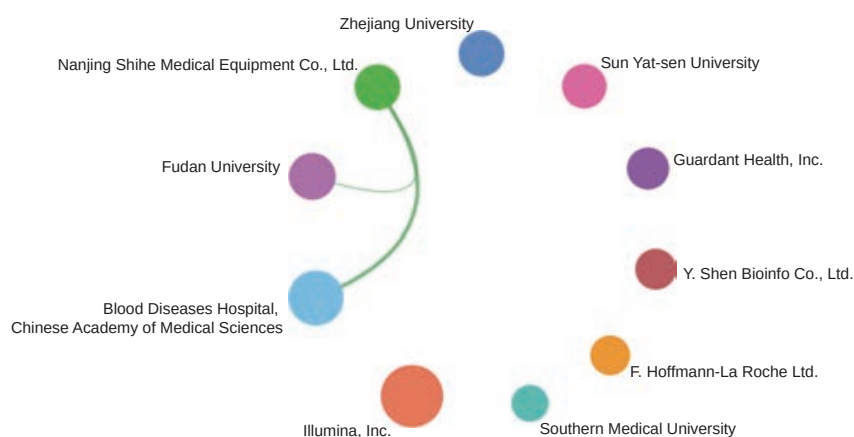


Figure 9.16 Collaboration network among institutions in the engineering development front of “artificial intelligence-assisted early screening and diagnosis of cancer”

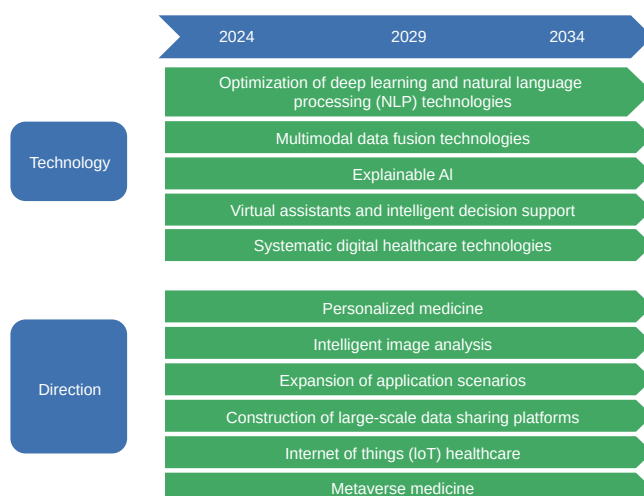


Figure 9.17 Roadmap of the engineering development front of "artificial intelligence-assisted early screening and diagnosis of cancer"

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Chapter 10 Engineering Management Fronts



10.1 Engineering research fronts

10.1.1 Trends in the Top 10 engineering research fronts

In the field of engineering management, the global Top 10 engineering research fronts this year are “research on the optimization of engineering management based on generative artificial intelligence”, “long-term impact of machine behavior and large AI models on human decision-making”, “modeling and enhancing resilience in urban physical-information-social systems”, “comprehensive optimization and evaluation of green energy systems”, “research on digital carbon emission monitoring, calculation methods, and spatiotemporal feature evolution”, “public risk perception in complex social information networks”, “research on the digital twin model simulation and virtual-physical interaction methods for buildings”, “research on supply chain management and optimization strategies under the carbon neutrality goal”, “research on climate finance asset pricing and risk management”, and “ethical research on generative AI algorithms”.

Citations to seminal articles pertinent to these topics can be found in Tables 10.1 and 10.2. Among these domains, particular attention is accorded to “research on the optimization of engineering management based on generative artificial intelligence”, “long-term impact of machine behavior and large AI models on human decision-making”, “modeling and enhancing resilience in urban physical-information-social systems”, and “comprehensive optimization and evaluation of green energy systems”. Succeeding sections will offer a robust analysis of their extant developmental trajectories and prospective orientations.

(1) Research on the optimization of engineering management based on generative artificial intelligence

With the rapid advancement of technology and the increasing complexity of projects, engineering management is vital for

Table 10.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Research on the optimization of engineering management based on generative artificial intelligence	18	455	25.28	2021.3
2	Long-term impact of machine behavior and large AI models on human decision-making	43	578	13.44	2020.9
3	Modeling and enhancing resilience in urban physical-information-social systems	8	204	25.50	2021.1
4	Comprehensive optimization and evaluation of green energy systems	30	1 474	49.13	2019.3
5	Research on digital carbon emission monitoring, calculation methods, and spatiotemporal feature evolution	23	833	36.22	2020.3
6	Public risk perception in complex social information networks	29	765	26.38	2020.9
7	Research on the digital twin model simulation and virtual-physical interaction methods for buildings	29	627	21.62	2021.0
8	Research on supply chain management and optimization strategies under the carbon neutrality goal	20	419	20.95	2022.2
9	Research on climate finance asset pricing and risk management	16	637	39.81	2021.2
10	Ethical research on generative AI algorithms	16	140	8.75	2022.7

Table 10.2 Annual number of core papers published for the Top 10 engineering research fronts in engineering management

No.	Engineering research front	2018	2019	2020	2021	2022	2023
1	Research on the optimization of engineering management based on generative artificial intelligence	1	3	2	1	5	6
2	Long-term impact of machine behavior and large AI models on human decision-making	4	7	4	11	8	9
3	Modeling and enhancing resilience in urban physical-information-social systems	1	1	1	0	3	2
4	Comprehensive optimization and evaluation of green energy systems	1	2	2	0	3	5
5	Research on digital carbon emission monitoring, calculation methods, and spatiotemporal feature evolution	2	8	3	4	4	2
6	Public risk perception in complex social information networks	3	3	2	12	4	5
7	Research on the digital twin model simulation and virtual-physical interaction methods for buildings	3	6	2	4	5	9
8	Research on supply chain management and optimization strategies under the carbon neutrality goal	0	0	1	2	8	9
9	Research on climate finance asset pricing and risk management	2	1	2	3	2	6
10	Ethical research on generative AI algorithms	0	0	0	2	1	13

ensuring smooth progress and successful project completion. Modern engineering projects typically involve collaboration among multiple parties, resource allocation, and risk control, which require managers to have comprehensive professional knowledge and management skills. However, challenges in fully implementing ideas and concepts, along with real-world constraints, create a significant gap between the actual performance of engineering management and the expected results. This gap can lead to project delays, budget overruns, and may impact the quality and safety of engineering projects.

Against this backdrop, the disruptive developments in generative artificial intelligence (AI) present an opportunity to transform engineering management. Although the application of generative AI in optimizing engineering management is still in the early stages of integration and basic application, it has already demonstrated significant potential. These technologies, through advanced data analysis, predictive modeling, and automated processes, offer more scientific and efficient solutions in areas such as engineering consulting, marketing, and operations.

(2) Long-term impact of machine behavior and large AI models on human decision-making

With the rapid advancement of intelligent technologies, machines are becoming central actors in both everyday work and life, gaining increasing importance. The study of machine behavior—examining the actions exhibited by intelligent machines—has attracted considerable attention and further research since its inception. The widespread and diverse applications of intelligent machines, particularly with the emergence of large generative AI models like ChatGPT, have led these systems to exert a growing influence on human behavior across various levels.

Previous studies have not only conducted empirical research to collect and analyze data validating the effectiveness of human-machine collaborative decision-making but have also investigated the factors influencing the decision-making process in human-machine interactions. These factors include communication patterns, task allocation, and role definition. Drawing from findings in cognitive science, researchers have explored how an understanding of human cognitive processes can enhance the collaborative efficiency of human-machine systems. They have also examined ways to integrate human intuition, judgment, and decision-making abilities with the data processing, pattern recognition, and learning capabilities of machines to achieve more efficient and

accurate decision-making.

Building on these studies, further guidance has been developed for the implementation of human-machine interaction systems, enabling machines to comprehend and respond effectively to human instructions and needs while allowing human users to monitor and guide machine behavior proficiently. Moreover, research has expanded to address how ethical principles can be maintained in human-machine collaborative decision-making, as well as how to balance technological advancements with social responsibility.

(3) Modeling and enhancing resilience in urban physical-information-social systems

Cities are dynamic organisms that evolve over time due to the interaction among the natural environment, built environment, infrastructures, and the social environment—human activity—that occur within those contexts. As cities rapidly urbanize and natural disasters increase in frequency, urban resilience—the capacity of urban systems to sustain or return quickly to functional status in times of disruption—is invaluable for sustainable development. Cities can be viewed as a “three-dimensional space” composed of physical (tangible elements), informational (data), and social (human activities) dimensions. The subsystems within the three dimensions interact to support urban function, and collectively, the resilience of these three dimensions—and their ability to sustain or recover quickly from natural disasters—provides a city’s resilience.

In addition, as urban systems become increasingly complex, disasters in the natural environment can produce aftereffects. These are often seen through “inter-system transmission” or “cross-dimensional diffusion”. For example, the natural disaster may damage the power grid disrupting the water system and communication system, which damages the functionality of critical social services such as hospitals. However, research and practice have primarily focused on subsystems individually as a way of understanding interactions and explain the incident in the interactions between the dimensions and the social. Therefore, identifying infrastructure elements that require priority protection or allocating limited resources for disaster prevention and mitigation across urban subsystems is inefficient.

In this manner, cross-dimensional modeling centers on urban physical, information, and social systems in connection with urban resilience building. Cross-dimensional modeling has become a new frontier in urban resilience research. The current research focuses on the intersection of these dimensions in the following ways to improve and model urban resilience. First, modeling of information-physical systems utilizes real-time data collected from cloud computing and big data analysis to create safer, more stable urban physical systems. Second, modeling social-information systems examines behaviors associated with social life and how information is distributed to enhance emergency resource allocation and self-organization in communities, thereby improving urban system response capacity in a disaster. Third, physical-social system modeling engages with the layered interaction between physical systems and social systems to view complex dynamic aspects of the systems during a disaster, improving the accuracy of emergency management and risk assessments.

Ultimately, cross-dimensional modeling allows evaluation of urban resilience from a scenario-based perspective to create responses for resilience optimization of systems impacted by a concentrated stress. Future studies will examine co-evolutionary mechanisms among physical-information-social systems as the crux for integrated resilience building and foster innovation across disciplines and compartments. Examples of possible topics could include exploring data security, intelligence, integrated modeling for system resilience, and precision modeling as a maximizing value proposition of existing and emerging technologies for urban resilience.

(4) Comprehensive optimization and evaluation of green energy systems

In the context of global energy transition and sustainable development, the comprehensive optimization and evaluation of green energy systems have become essential for addressing climate change, ensuring energy security, and promoting environmental protection. By integrating renewable energy technologies, green energy systems not only reduce the reliance on traditional fossil fuels but also enable the efficient use of multiple energy sources and foster low-carbon development. A central focus of this research is optimizing overall performance while balancing economic viability, reliability, and environmental sustainability.

On one hand, as the penetration of renewable energy continues to rise, the integration and optimization of multi-energy systems face significant challenges. Although multi-energy conversion and diverse energy storage technologies have enhanced operational flexibility and energy efficiency, they have also increased the complexity of system operations and posed challenges to system stability. Consequently, developing efficient optimization strategies and multi-dimensional evaluation metrics to achieve coordinated multi-energy dispatch while minimizing lifecycle costs across energy production, transmission, storage, and consumption remains a critical research priority.

On the other hand, green hydrogen is rapidly emerging as a vital energy carrier for the future. Breakthroughs in hydrogen production, storage, and application technologies are providing essential support for the development of new low-carbon energy systems. Researchers are actively exploring cost-effective methods for green hydrogen production, efficient system optimization approaches, and comprehensive evaluation metrics to facilitate the deep integration of green hydrogen into future energy systems.

Recent research efforts have concentrated on the advanced modeling of electricity-heat-gas (hydrogen) conversion facilities within green energy systems. Key focus areas include evaluating green hydrogen production and integrated energy systems, optimizing the operation of electricity-heat-gas (hydrogen) systems, and planning for multi-network systems. Other priorities are designing market mechanisms and promoting sustainable development policies.

(5) Research on digital carbon emission monitoring, calculation methods, and spatiotemporal feature evolution

In 1958, the long-term observation of atmospheric carbon dioxide at the Mauna Loa Observatory in Hawaii was the first to confirm that carbon dioxide concentrations were rising year by year. From the 1970s to the 1990s, the concept of carbon emissions took shape, mainly through rough estimates of energy consumption and industrial activity statistics, with a focus on their impact on global climate change. In the 21st century, satellite remote sensing technology has been introduced into the field of carbon monitoring, and quantitative analysis tools such as life cycle assessment and carbon footprint model have been developed. Since 2010, advances in information technology have promoted the application of sensor networks, big data and cloud computing in carbon emission monitoring, and enhanced the research on the spatial-temporal evolution characteristics of carbon emissions. After 2020, with the rapid development of big data and artificial intelligence, the monitoring and management of carbon emissions in key industries will gradually be digitized, and the research focus will shift to improving the accuracy and spatial and temporal resolution of carbon emission inventories, as well as exploring the complex relationship between carbon emissions and multiple factors such as economy, society, environment, and policy.

Current research on carbon emission monitoring primarily emphasizes the innovation and application of several key technologies. The integration of the internet of things (IoT) and digital twin technology facilitates real-time collection of carbon emission data through IoT devices. Meanwhile, digital twins provide precise mapping and trend forecasting, which enhance the accuracy of carbon emission calculations and evaluations. Additionally, an integrated sky-space-ground monitoring approach, utilizing digital Earth platforms, combines satellite, drone, and ground-based monitoring data to form a high-resolution, near-real-time panoramic carbon emission monitoring network. The incorporation of supercomputing and intelligent analytics enables efficient data analysis and in-depth pattern mining, thus enhancing intelligent carbon emission management and decision-making. These technological advancements are propelling carbon emission monitoring toward comprehensive, accurate, and intelligent development.

Current research on carbon emission monitoring primarily emphasizes the innovation and application of several key technologies. The integration of the IoT and digital twin technology facilitates real-time collection of carbon emission data through IoT devices. Meanwhile, digital twins provide precise mapping and trend forecasting, which enhance the accuracy of carbon emission calculations and evaluations. Additionally, an integrated sky-space-ground monitoring approach, utilizing digital Earth platforms, combines satellite, drone, and ground-based monitoring data to form a high-resolution, near-real-time panoramic carbon emission monitoring network. The incorporation of supercomputing and intelligent analytics enables efficient data analysis and in-depth pattern mining, thus enhancing intelligent carbon emission management and decision-making. These technological advancements are propelling carbon emission monitoring toward comprehensive, accurate, and intelligent development.

Over the next decade, our objective for carbon emission monitoring is to establish a multi-interface, multi-source, integrated, and

visually comprehensive network that encapsulates the “sky-space-ground-sea-human” framework, all while maintaining high spatiotemporal resolution. At the heart of this initiative will be a dynamic carbon data platform that seamlessly integrates multi-source and multi-scale data, becoming an intrinsic part of intelligent energy systems. This sophisticated system will unify various monitoring tools, including satellites, ground stations, drones, and vehicle-mounted devices, to create a dynamic carbon flux network characterized by enhanced spatiotemporal resolution. In comparison to current carbon flux networks, this advanced carbon-energy system is expected to vastly improve both the accuracy and resolution of carbon flow monitoring. Furthermore, it will significantly enhance our capacity to inform energy network planning and operations. This adaptability will be vital for achieving long-term, large-scale carbon neutrality objectives while navigating the complexities of carbon-neutral energy network development and operation.

(6) Public risk perception in complex social information networks

Public risk perception refers to the public’s concern or anxiety regarding specific issues and includes the subjective evaluation process of particular risk conditions. With the rapid advancement of information technologies such as big data, large models, and high computing power, the dissemination of information related to emergencies or risk factors is increasingly influenced by artificial intelligence-generated content (AIGC) and various social media platforms. In the current complex social information network environment, public risk perception regarding certain topics exhibits new characteristics and patterns. Significant progress has been achieved in the study of public risk perception within complex social information networks across various disciplines, including management, disaster science, sociology, computer science, data science, engineering, and communication. This research highlights new features such as the dynamic, interconnected, complex, and ambiguous nature of public risk perception. Current studies frequently employ automated methods to collect multi-source, heterogeneous open-source data from the internet, aggregating information from social platforms, news media, e-commerce websites, and geographic resources. These investigations analyze information diffusion patterns and networks related to major emergencies, emerging technologies, specific social or policy topics, as well as the characteristics and evolution of public risk perception and the risk intervention strategies employed by responsible entities.

Future research trends in this field include: ① Exploring the diffusion patterns of risk information and the interactive effects of risk perception based on differences in risk cognition across heterogeneous network communities. ② Analyzing the relationship between risk information presentation using AIGC, public risk perception, and trust levels. ③ Developing information mining techniques and quantitative models for public risk perception based on multi-source heterogeneous data. ④ Investigating the evolution of public risk perception in response to different types of emergencies, major projects, and emerging technology trends, along with panoramic information presentation methods. This will form the basis for developing information communication strategies through multi-source information platforms.

(7) Research on the digital twin model simulation and virtual-physical interaction methods for buildings

A digital twin consists of a virtual representation of the physical world within a digital space, enabling real-time analysis and intelligent decision-making through the integration of digital sensing, transmission, and AI technologies. Insights generated from analyzing extensive physical data are reintegrated into the physical world, permitting continuous optimization and informed decision-making. Since its inception in 2003, digital twin technology has been extensively utilized in aerospace and industrial manufacturing and has swiftly expanded into the operation and management of urban buildings and building clusters.

Currently, the development of digital twins for buildings (or clusters) primarily relies on the integration of various technologies, including city information modeling (CIM), building information modeling (BIM), geographic information systems (GIS), IoT, and AI. The maturity of digital twins can be categorized into six levels: Level 1 (virtual simulation of the real), Level 2 (virtual reflection of the real), Level 3 (virtual control of the real), Level 4 (virtual prediction of the real), Level 5 (virtual optimization of the real), and Level 6 (virtual-real symbiosis). Among these levels, Levels 3–5, which include digital twin model simulation and virtual-physical interaction, represent the core challenges that require significant breakthroughs.

In recent years, research in this domain has been in its nascent stages, focusing on the integration of information collection

and analysis, the construction of digital twin models, and the design of hardware and software for facilitating virtual-physical interaction. Prominent examples include the application of computer vision and IoT in construction safety training, human-machine-environment interaction through virtual reality, and the control of building equipment utilizing big data. In contrast, countries such as the USA and various European nations have developed more advanced urban digital twin systems, having established comprehensive strategic frameworks and foundational standards. Initiatives such as “Virtual Singapore”, supported by leading companies like Autodesk, exemplify cutting-edge exploratory practices in this field.

As the demand for smart city development increases and information technology advances, the potential for digital twin technology in buildings and clusters is becoming increasingly promising. Future research trends are likely to focus on developing technical frameworks for building digital twins, creating proprietary digital twin platforms, and applying high-efficiency sensing, complete element recognition and tracking, model reconstruction, updates, and simulation-based control in various areas such as construction and renovation, energy consumption regulation, service safety, and disaster prevention and emergency response.

(8) Research on supply chain management and optimization strategies under the carbon neutrality goal

In recent years, “research on supply chain management and optimization strategies under the carbon neutrality goal” has been a key focus for scholars both domestically and internationally. The research primarily considers the impact of carbon neutrality targets, focusing on the following five major areas.

1) Emission reduction decisions and optimization strategies in supply chains under carbon trading policies. Carbon trading policies affect manufacturers and consumers in the supply chain differently. While benefiting consumers, these policies reduce manufacturers’ surplus but contribute to overall social welfare. With the introduction of the “carbon neutrality” strategy, consumer awareness of low-carbon production has increased, and government carbon trading mechanisms and low-carbon consumption subsidies are gradually being implemented, providing favorable opportunities for enterprises. Nonetheless, how governments can develop appropriate carbon trading policies and how companies can make optimal low-carbon production decisions within supply chains remain key challenges in the research on low-carbon transition and development.

2) Impact of carbon trading policy-driven innovation in supply chain carbon reduction technologies. The most fundamental way to achieve corporate carbon reduction is through investment in and innovation of carbon reduction technologies. Under carbon trading policies, supply chain members face decisions on technology investment and strategies for vertical collaboration. Carbon trading policies impose stricter conditions for vertical collaboration. However, the impact mechanisms of carbon trading policy-driven innovation on inter-enterprise cooperation, resource sharing, optimization of supply chain cost-benefit efficiency in carbon reduction, supply chain regulation, and information disclosure are still unknown and represent important future research directions.

3) Financing models for low-carbon supply chains. The evolution of the low-carbon economy has intensified concerns about financial constraints within low-carbon supply chains. This is particularly evident in areas such as corporate transformation, green product R&D, green product promotion, and other environmentally friendly activities that require financial support. Collaborative financing among various stakeholders in low-carbon supply chains can not only increase the availability of low-carbon products for consumers but also improve supply chain profitability and overall performance. However, capital constraints often diminish profits for suppliers while simultaneously boosting profits for retailers. Additionally, financing decisions are significantly impacted by varying low-carbon investment cost coefficients and production costs. Therefore, given the constraints imposed by carbon emissions, further research is necessary to explore how to create a win-win scenario that balances social welfare with manufacturers’ profits across different financing models.

4) Implementation barriers of digital and carbon reduction technologies in low-carbon supply chains. Digital and carbon reduction technologies empower companies within the supply chain to effectively manage processes related to carbon tracking, analysis, and reduction. Nevertheless, substantial barriers hinder the implementation of these technologies in low-carbon supply chains, particularly the challenges associated with collecting and calculating carbon emission data.

5) Network design and optimization of low-carbon supply chains. Under the context of carbon neutrality development, the key

challenge in designing low-carbon supply chain networks is how to maximize supply chain network benefits while minimizing carbon emissions. Factors such as the selection of strategic supply chain partners, logistics scheduling, energy resource selection and utilization, and inventory management must all be carefully considered in the design of low-carbon supply chain networks. Therefore, there is a pressing need for further attention to optimized design methods aimed at maximizing the comprehensive benefits for companies involved in constructing low-carbon supply chain logistics networks.

(9) Research on climate finance asset pricing and risk management

Climate change not only directly impacts natural ecosystems but also presents significant threats to global economic development and the stability of financial systems. Climate finance refers to all financial activities globally that aim to mitigate and adapt to climate change, thereby supporting the green, low-carbon transformation of the economy and society to achieve sustainable development. The focus of climate finance research lies in accurately characterizing physical risks (e.g., extreme weather events) and transition risks (e.g., economic restructuring resulting from policy changes, technological innovations, or shifts in consumer preferences) associated with climate change. It investigates how to price financial assets subject to climate risks and evaluates the management of the various financial risks arising from these climate exposures.

In-depth research on climate finance asset pricing and risk management is essential for maintaining financial stability and fostering sustainable global economic development. Current research explores the following areas: ① Quantification and assessment of climate risks. This involves estimating asset losses stemming from extreme climate events through natural disaster monitoring technologies, assessing stranded asset risks and their implications for financial stability, and developing climate risk-related indices at both market and company levels using methodologies such as text analysis and machine learning. ② Climate risk and asset pricing. This research investigates how physical and transition risks induced by climate change influence the pricing of various asset classes, including real estate, stocks, and fixed-income securities. ③ Climate risk management and investment strategy optimization. This domain examines how financial institutions address climate risk through stress testing and the innovation of financial instruments. It also investigates how investors can develop portfolios that effectively hedge against climate risk and how governments can enact financial policies to avert and mitigate the repercussions of climate risk on economic and financial stability.

Emerging research trends in this area include the detailed measurement of climate risk utilizing multi-source heterogeneous data, the creation and equitable pricing of new climate finance tools, the exploration of the interconnected relationships and feedback loops between climate finance systems and socio-economic systems, and the establishment of innovative international cooperation mechanisms for climate risk management.

(10) Ethical research on generative AI algorithms

Generative AI represents a vital branch within the field of AI. Utilizing technologies such as deep learning, probabilistic models, and generative adversarial networks, it learns and simulates data patterns to create content, including text, audio, video, and code, greatly enhancing productivity. However, as generative AI sees increased application in fields such as media production and healthcare, the ethical issues arising during its use have become a focal point of societal concern. Current ethical research primarily addresses the following areas.

First, AI development and training raise issues related to data collection, training content, development costs, and the ethical biases of developers. In particular, AI data collection raises concerns about surveillance and the commercialization of personal data, especially in sensitive areas like healthcare. The quality of data, training methods, and developers' ethical perspectives significantly affect AI-generated content, often leading to bias. As a result, ethical education and interdisciplinary training for developers have become central topics in ethics research. Second, AI application concerns focus on the misuse of AI technology and human-AI collaboration. Misuse mainly involves creating and spreading false information. The debate on human-AI collaboration questions whether AI is just a tool or a creator, whether its output is truly innovative, and whether AI can be considered morally accountable.

Future research will explore deeper aspects of human-AI collaboration and integration. Key topics will include responsibility-sharing between humans and AI, defining and punishing virtual crimes, identity and recognition in human-AI integration, and the value of agency.

10.1.2 Interpretations for four key engineering research fronts

10.1.2.1 Research on the optimization of engineering management based on generative artificial intelligence

“Research on the optimization of engineering management based on generative artificial intelligence” focuses on the entire lifecycle of engineering projects, concentrating on six key areas. ① Engineering consulting: Utilizing generative AI to offer consulting support regarding policies, regulations, and human resources. ② Engineering marketing: Supporting marketing, after-sales, and other business operations. ③ Engineering operations: Facilitating intelligent personnel scheduling. ④ Financial auditing: Ensuring compliance with legal and regulatory standards for engineering projects. ⑤ Risk management: Employing generative AI to assess project risks in real-time and recommend preventive actions. ⑥ Research and development: Assessing the feasibility of designs and addressing technical challenges.

According to Table 10.3, the leading six countries in publishing core papers on “research on the optimization of engineering management based on generative artificial intelligence” are China, Australia, the USA, France, the UK, and Germany. The principal institutions contributing to this research include IMT Atlantique, Korea Advanced Institute of Science and Technology, and Sookmyung Women’s University (Table 10.4). The research findings indicate that the

Table 10.3 Countries with the greatest output of core papers on “research on the optimization of engineering management based on generative artificial intelligence”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	6	33.33	30	5.00	2020.0
2	Australia	2	11.11	195	97.50	2022.0
3	USA	2	11.11	22	11.00	2020.5
4	France	2	11.11	18	9.00	2023.0
5	UK	2	11.11	5	2.50	2019.5
6	Germany	2	11.11	1	0.50	2023.0
7	Republic of Korea	1	5.56	188	188.00	2019.0
8	Belgium	1	5.56	18	18.00	2023.0
9	Greece	1	5.56	18	18.00	2023.0
10	Ireland	1	5.56	18	18.00	2023.0

Table 10.4 Institutions with the greatest output of core papers on “research on the optimization of engineering management based on generative artificial intelligence”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	IMT Atlantique	2	11.11	18	9.00	2023.0
2	Korea Advanced Institute of Science and Technology	1	5.56	188	188.00	2019.0
3	Sookmyung Women’s University	1	5.56	188	188.00	2019.0
4	Monash University	1	5.56	184	184.00	2022.0
5	University of Melbourne	1	5.56	184	184.00	2022.0
6	Victoria University	1	5.56	184	184.00	2022.0
7	Western Sydney University	1	5.56	184	184.00	2022.0
8	University of Chicago	1	5.56	22	22.00	2019.0
9	Nanjing Forestry University	1	5.56	20	20.00	2022.0
10	Nanjing Xiaozhuang University	1	5.56	20	20.00	2022.0

distribution of studies in this area is concentrated in Asia and Europe, with significant collaboration between France and countries like Belgium, Greece, and Ireland (Figure 10.1). In terms of institutional cooperation, most collaborations occur between universities within the same country, with active partnerships among universities in Australia and Canada. Notable partnerships include Monash University, the University of Melbourne, Victoria University, and Western Sydney University (Figure 10.2). As shown in Table 10.5, China ranks first in terms of the number of citing papers. Table 10.6 indicates that the top three institutions for citing papers are Massachusetts Institute of Technology, Tsinghua University, and Chongqing University.

Figure 10.3 illustrates the roadmap of “research on the optimization of engineering management based on generative artificial intelligence”. This initiative is driven by the pressing need to expedite the application of generative AI, establish intelligent engineering management platforms, and integrate the design process with engineering management. Continuous advancements are being made in the development of frameworks, technologies, operational standards, and management systems. The ultimate goal of this progressive approach is to achieve intelligent management of engineering projects, facilitating efficient resource utilization and optimal allocation.

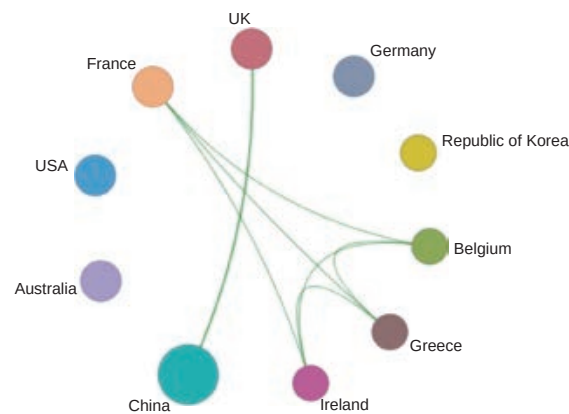


Figure 10.1 Collaboration network among major countries in the engineering research front of “research on the optimization of engineering management based on generative artificial intelligence”

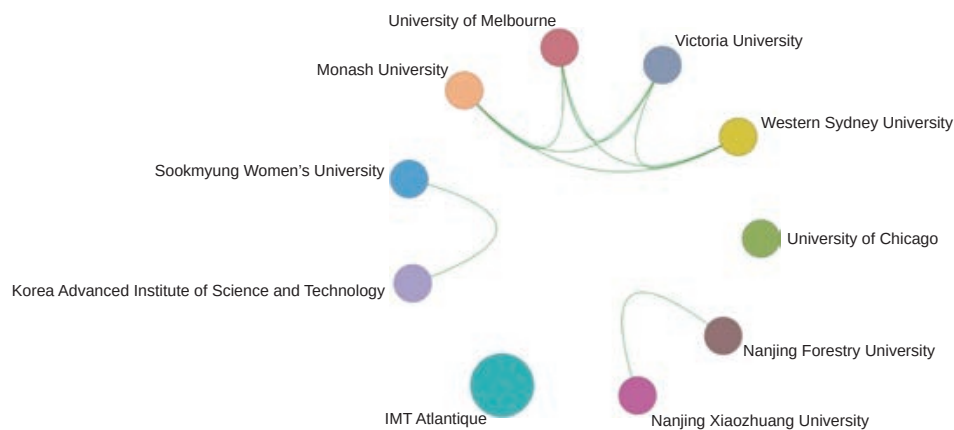


Figure 10.2 Collaboration network among major institutions in the engineering research front of “research on the optimization of engineering management based on generative artificial intelligence”

Table 10.5 Countries with the greatest output of citing papers on “research on the optimization of engineering management based on generative artificial intelligence”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	113	24.84	2023.1
2	USA	87	19.12	2022.2
3	Republic of Korea	23	5.05	2022.6
4	India	18	3.96	2023.4
5	Australia	18	3.96	2023.3
6	Germany	15	3.30	2022.7
7	Canada	12	2.64	2023.3
8	Malaysia	8	1.76	2023.1
9	Sweden	8	1.76	2023.4
10	Italy	8	1.76	2022.5

Table 10.6 Institutions with the greatest output of citing papers on “research on the optimization of engineering management based on generative artificial intelligence”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Massachusetts Institute of Technology	11	2.42	2021.7
2	Tsinghua University	7	1.54	2022.3
3	Chongqing University	6	1.32	2023.2
4	Beijing University of Technology	6	1.32	2023.0
5	National University of Defense Technology	5	1.10	2022.6
6	University of Texas at Austin	5	1.10	2022.2
7	Technical University of Munich	5	1.10	2022.4
8	Chinese Academy of Sciences	4	0.88	2022.8
9	Georgia Institute of Technology	4	0.88	2022.8
10	Tongji University	4	0.88	2022.5

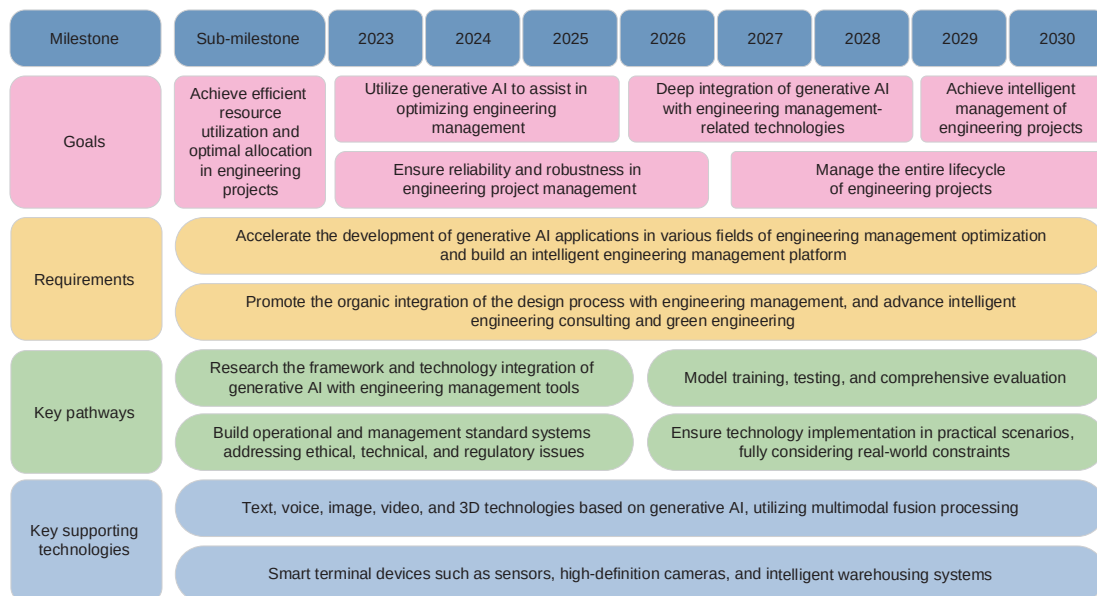


Figure 10.3 Roadmap of the engineering research front of “research on the optimization of engineering management based on generative artificial intelligence”

10.1.2.2 Long-term impact of machine behavior and large AI models on human decision-making

The exploration of the “long-term impact of machine behavior and large AI models on human decision-making” is anticipated to exhibit trends that are increasingly diverse, in-depth, and focused on practical applications. Future research will prioritize interdisciplinary integration, multi-dimensional analysis, long-term consequences, and dynamic shifts. Additionally, it will stress the importance of ethical and legal considerations, alongside the development of pertinent policies and regulations. Specifically:

(1) Enhanced human-machine collaborative decision-making

In various industries, such as financial investment and medical diagnostics, as well as in scenarios like disaster response and medical emergencies, large AI models harness their data processing capabilities to identify complex patterns and trends. This advancement enables humans to receive more precise predictions and recommendations, thereby improving the efficiency and quality of decision-making. From an interaction perspective, research will concentrate on enhancing the collaboration between humans and machines, exploring how AI can elevate the quality of interactions and how these interactions influence decision-making processes. Furthermore, studies will evaluate the collaborative capabilities of AI-assisted systems in complex tasks and their effect on the efficiency and accuracy of human decision-making. On the machine side, research will aim to enhance the explainability of AI systems, ensuring users can comprehend their decision-making logic and recommendations. This exploration will also consider how transparency influences long-term user trust and decision-making behaviors. Sociologically, studies will investigate the role of intelligent machines and decision systems in reshaping social structures, including employment and economic patterns, as well as how these changes affect human decision-making and social interactions.

(2) Human-machine organization and task allocation in decision-making

This research focuses on how machines can manage standardized and repetitive decision-making processes to minimize human error, allowing individuals to concentrate on decisions that necessitate creative and strategic thinking. It examines the influence of such systems on human decision processes, decision quality, and overall satisfaction with decisions. Additionally, the study will investigate psychological transformations experienced by humans during human-machine interactions, such as trust, dependency, and self-perception, and how these changes impact decision-making behaviors. When warranted, AI systems can dynamically adjust to assume portions of decision-making tasks, thereby alleviating cognitive load and enabling decision-makers to focus on higher-level considerations. Moreover, the organization and coordination of human-machine collaboration (e.g., how responsibilities, rights, and duties are distributed) has emerged as a crucial research area. Shifts in decision-making models arising from human-machine collaboration are also under investigation, particularly the potential long-term reliance on AI for decision support, which may alter human decision-making patterns. Individuals may increasingly favor data-driven decisions over reliance solely on experience or intuition, although this shift could also lead to over-dependence on machines, potentially resulting in cognitive decline.

(3) Ethical and responsibility issues in decision-making

As the role of AI in decision-making expands, ethical concerns and the assignment of responsibility become increasingly complex, particularly when AI-generated recommendations result in adverse outcomes. Establishing accountability in these scenarios has emerged as a critical area of focus. Additionally, there is a growing emphasis on privacy protection when intelligent machines and decision systems collect, process, and utilize personal data. There is a pressing need for research to enhance data security and privacy protection technologies to safeguard individual privacy against potential threats. Moreover, examining the legal and ethical frameworks governing the role of intelligent machines and decision systems, such as responsibility attribution and rights protection, is essential to provide legal and ethical guidance for the responsible development of technology.

(4) Adaptation of skills and education

Over the long term, collaboration between humans and AI is expected to cultivate new work models and organizational structures, necessitating that individuals adapt to environments where they work alongside intelligent machines. To proficiently employ AI in decision-making, humans will need to acquire new skills and knowledge, prompting reforms in education and vocational training systems. Research should investigate how AI alters workflows and job roles, as well as explore how AI can enhance education and training processes to promote human development. It is also necessary to evaluate the impact of AI on employee satisfaction, job performance, and career growth. Furthermore, research should examine the effects of AI systems on users' mental health—such as stress, anxiety, and decision fatigue—while exploring AI's potential for providing psychological support and intervention, ultimately fostering positive human-machine interactions at the organizational level.

(5) Policy and regulation

The widespread integration of AI in decision-making is likely to transform labor market demands, resulting in shifts within societal structures and labor markets. Consequently, it is crucial to design and implement long-term studies to monitor and assess the ongoing influence of AI on human decision-making at both the individual and societal levels. Additional research is needed to develop effective policies and regulations that manage the use of AI in decision-making processes, ensuring positive outcomes while minimizing any potential negative consequences.

As illustrated in Tables 10.7 and 10.8, the USA, China, and Germany are ranked as the top three countries in terms of the volume of core papers addressing the “long-term impact of machine behavior and large AI models on human decision-making”. Key institutions contributing to these core papers include Georgia Institute of Technology and Nanyang Technological University. The collaboration network among major countries (Figure 10.4) indicates that the United States engages in extensive collaboration with other nations, followed by China, Singapore, and Australia. In terms of institutional collaboration (Figure 10.5), Nanyang Technological University, the Hong Kong Polytechnic University, Georgia Institute of Technology, and University of Macau are noted for their close cooperation. Regarding citation impact, Table 10.9 reveals that China leads in the number of highly cited core papers, with the Hong Kong Polytechnic University and Tsinghua University being prominent institutions (Table 10.10).

Table 10.7 Countries with the greatest output of core papers on “long-term impact of machine behavior and large AI models on human decision-making”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	11	25.58	299	27.18	2019.9
2	China	9	20.93	135	15.00	2022.2
3	Germany	5	11.63	113	22.60	2020.0
4	UK	5	11.63	66	13.20	2020.4
5	Italy	4	9.30	59	14.75	2021.2
6	Singapore	3	6.98	129	43.00	2021.0
7	Australia	3	6.98	60	20.00	2020.3
8	Belgium	2	4.65	62	31.00	2022.0
9	Denmark	2	4.65	46	23.00	2020.5
10	Netherlands	2	4.65	6	3.00	2022.0

Table 10.8 Institutions with the greatest output of core papers on “long-term impact of machine behavior and large AI models on human decision-making”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Georgia Institute of Technology	2	4.65	74	37.00	2020.0
2	Nanyang Technological University	2	4.65	72	36.00	2021.0
3	Ghent University	2	4.65	62	31.00	2022.0
4	Zhejiang University	2	4.65	39	19.50	2021.5
5	University of Minnesota	1	2.33	97	97.00	2021.0
6	Saarland University	1	2.33	97	97.00	2021.0
7	The Hong Kong Polytechnic University	1	2.33	71	71.00	2021.0
8	University of Macau	1	2.33	71	71.00	2021.0
9	Massey University	1	2.33	67	67.00	2020.0
10	University of Canterbury	1	2.33	67	67.00	2020.0

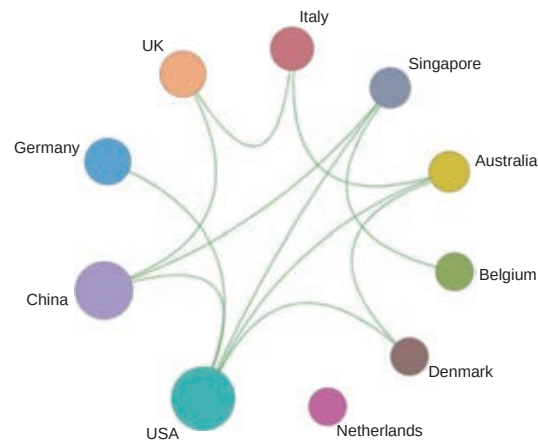


Figure 10.4 Collaboration network among major countries in the engineering research front of “long-term impact of machine behavior and large AI models on human decision-making”

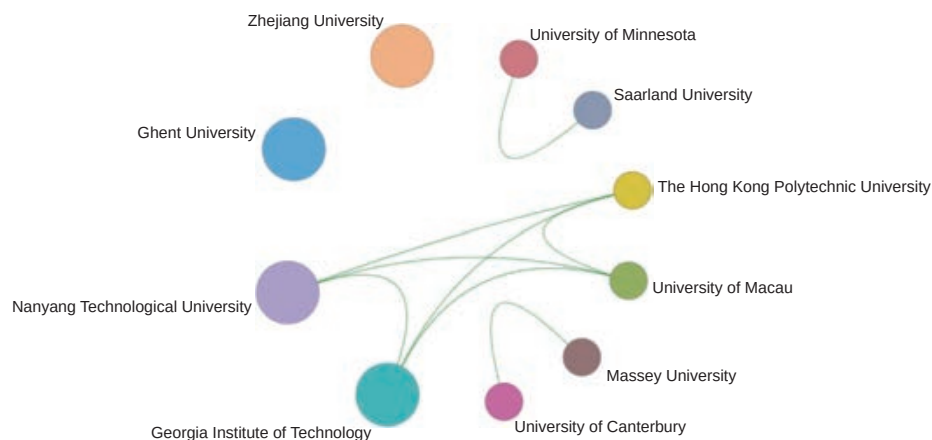


Figure 10.5 Collaboration network among major institutions in the engineering research front of “long-term impact of machine behavior and large AI models on human decision-making”

Figure 10.6 presents the roadmap of “long-term impact of machine behavior and large AI models on human decision-making”. Future research should aim to establish a human-machine integrated society, emphasizing various levels of human-machine collaboration, coordination, advancement, and harmonious coexistence. The research should prioritize enhancing human-machine interaction and refining algorithms, applying these insights to specific scenarios to foster mutual understanding. Additionally, studies should investigate the long-term societal effects of human-machine collaboration, informing the development of relevant laws and regulations, and promoting a future society characterized by human-machine symbiosis.

Table 10.9 Countries with the greatest output of citing papers on “long-term impact of machine behavior and large AI models on human decision-making”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	165	29.31	2022.5
2	USA	88	15.63	2022.2
3	Germany	70	12.43	2022.5
4	UK	51	9.06	2022.4
5	Australia	45	7.99	2022.4
6	Italy	37	6.57	2022.4
7	India	33	5.86	2022.3
8	Canada	23	4.09	2022.4
9	Netherlands	21	3.73	2022.4
10	Finland	15	2.66	2022.4

Table 10.10 Institutions with the greatest output of citing papers on “long-term impact of machine behavior and large AI models on human decision-making”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	The Hong Kong Polytechnic University	16	18.82	2022.1
2	Tsinghua University	11	12.94	2022.4
3	Massey University	8	9.41	2021.6
4	National University of Singapore	7	8.24	2022.9
5	Curtin University	7	8.24	2022.6
6	Syracuse University	6	7.06	2021.2
7	Tongji University	6	7.06	2022.3
8	University of Cambridge	6	7.06	2021.5
9	Sun Yat-sen University	6	7.06	2023.0
10	Eindhoven University of Technology	6	7.06	2022.7

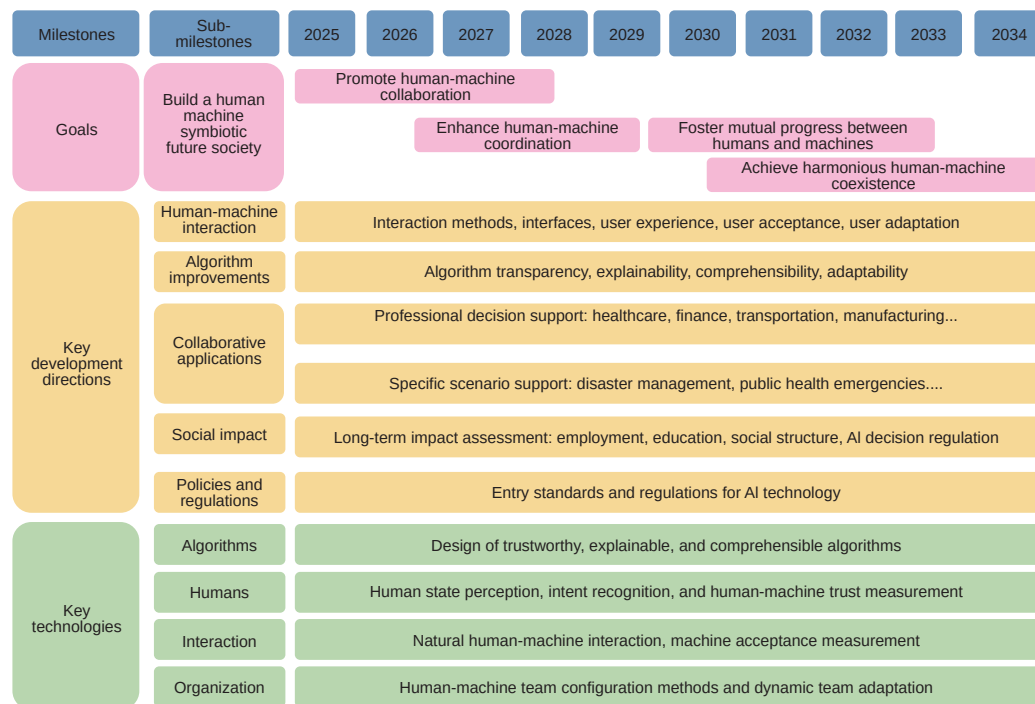


Figure 10.6 Roadmap of the engineering research front of “long-term impact of machine behavior and large AI models on human decision-making”

10.1.2.3 Modeling and enhancing resilience in urban physical-information-social systems

The primary research areas for “modeling and enhancing resilience in urban physical-information-social systems” include urban physical-information system modeling, urban social-information system modeling, urban physical-social system modeling, and urban resilience improvement. Specifically:

(1) Urban physical-information modeling

Research on physical-information modeling in urban systems aims to optimize resource allocation while ensuring the secure and stable operation of urban physical systems through the close integration of physical and information technologies. Current research and practices focus on two primary directions. First, real-time data from urban physical systems is collected through information systems and analyzed to model the operational status of these systems, thereby optimizing operational and maintenance strategies during emergencies. Second, attention is directed toward the cascading risks introduced by the coupling of physical and information systems. For instance, a city’s water supply system may be managed by a dispatch center to enhance efficiency. However, if this dispatch center is compromised by a cyberattack, the capacity of the water supply system can decrease significantly, disrupting normal urban operations. Consequently, the development of urban physical-information systems capable of resisting and recovering from cross-dimensional and cross-system risks has become a key research frontier. Researchers are exploring techniques like anomaly detection and proactive defense, which use real-time network monitoring to spot cyber threats. Alongside these, redundancy design and repair mechanisms are being developed to boost the fault tolerance of urban physical-information systems.

Looking ahead, urban physical-information modeling is expected to continue advancing toward smart technologies, with a focus on: ① improving the generalization capability of system models across different scenarios; ② developing digital twin technologies, such as city information modeling (CIM), as tools for managing urban resilience.

(2) Urban social-information modeling

Social-information modeling aims to characterize the dynamic responses of social systems under stress by utilizing data collected from urban information systems. This serves as a fundamental basis for enhancing urban resilience. Current research concentrates on employing big data and AI methodologies to model and analyze human behavioral patterns during and after disasters. By mining multi-source datasets, including social media posts and mobile network signaling data, researchers can map the spatiotemporal distribution and behavioral evolution of individuals and groups within a city, thereby gaining insights into the emergent mechanisms of social networks and collective behavior under stress.

Social information models can be applied throughout the entire urban resilience cycle: ① Pre-disaster: Analyzing historical data allows for the identification of high-risk areas and vulnerable populations, providing a foundation for targeted disaster mitigation policies. ② During a disaster: The model forecasts evacuation and migration trajectories of affected populations, optimizing the allocation of rescue resources and enhancing the efficiency of emergency response efforts. ③ Post-disaster: The model monitors the progress of reconstruction and the restoration of social order, offering decision support for resource allocation and priority adjustments.

Future research in urban social-information modeling will focus on: ① addressing security and privacy concerns in data collection and sharing within social systems, balancing the value of data with associated risks; ② developing collaborative social-information models that operate across levels and departments to facilitate effective data integration; ③ fostering innovation in collective behavior and social governance models based on social-information frameworks, enhancing public participation in resilience-building efforts both in breadth and depth.

(3) Urban physical-social system modeling

Urban physical-social system modeling seeks to uncover the interaction mechanisms between urban physical and social systems, emphasizing a human-centered approach to building resilient cities. Traditional physical models often struggle to encapsulate the feedback effects of human emergency behaviors and decision-making processes on urban physical subsystems, such as the impact of evacuation behavior on the transportation system. Physical-social modeling addresses this limitation by incorporating behavioral models and multi-agent systems, representing individual behaviors and the emergent characteristics and patterns of social systems derived from these interactions. This approach facilitates the analysis of the interplay between social and physical systems.

Researchers are integrating multi-source heterogeneous data, such as remote sensing, census data, and social surveys, to construct models that assess the effects of factors like building damage and traffic disruption on evacuations and economic losses during disasters. These models evaluate the impact of disasters on both physical and social systems, as well as the feedback effects of changes within the social system on physical systems. Some scholars are also exploring the application of AI techniques, including deep learning and reinforcement learning, to model individual and collective behavior in relation to risk perception, decision-making, and self-organization. These methods simulate the interactions between resident behavior and physical systems, as well as their changes over time and space, improving the model's ability to capture urban social processes during crises.

Additionally, growing research on social capital highlights how community networks and mutual aid positively affect post-disaster recovery and rebuilding. These studies have evolved the field of physical-social modeling from static representations to dynamic simulations. Future advancements in physical-social modeling will concentrate on: ① developing multi-scale methodologies to describe individual and collective behaviors, integrating data from diverse sources to enhance the understanding and characterization of various social behavior patterns; ② expanding the application of models beyond disaster emergency management to include broader domains, such as urban planning and infrastructure optimization; ③ exploring more generalizable theories of physical-social coupling mechanisms to improve the accuracy and applicability of models; ④ incorporating “human-in-the-loop” processes into modeling, engaging stakeholders in the development and application of these models.

(4) Enhancing urban system resilience

The primary aim of urban resilience research is to translate theoretical models into practical applications that bolster cities' capacity to respond to diverse shocks. Current research and practice emphasize the development of urban systems that take into account the interactions between physical, informational, and social frameworks. Through scenario-based simulations, researchers assess the dynamic characteristics of urban systems under various external shock scenarios, including the interdependencies of critical infrastructure and the prediction of cascading failure risks. These evaluations provide a crucial foundation for decision-making aimed at enhancing resilience.

Based on scenario analysis, techniques such as multi-criteria decision analysis and economic benefit assessments are employed to formulate strategies for improving the resilience of key components, optimizing resource allocation, and managing emergency responses. Additionally, these methods focus on strengthening supply chain resilience under stress and promoting interdepartmental and interregional cooperation. However, as urban systems become increasingly complex and new risks emerge and converge, existing models face limitations in addressing the complex challenges posed by multiple shocks.

Future research will concentrate on developing more comprehensive and generalizable urban system models to facilitate more accurate decision-making for enhancing resilience. This will include: ① creating integrated models that connect physical, informational, and social dimensions to fully simulate urban system responses to complex shocks; ② investigating methods for evaluating urban system resilience under complex risk scenarios.

In the front of “modeling and enhancing resilience in urban physical-information-social systems”, the USA, China, and Canada are the top three countries in terms of core paper output (Table 10.11). The primary institutions contributing to these core papers include the University of Hong Kong, Mississippi State University (the USA), and VSB-Technical University of Ostrava (Czech) (Table 10.12). As illustrated by the collaboration networks of major countries (Figure 10.7), China has closer cooperation with other countries. The collaboration among major institutions (Figure 10.8) reveals closer ties between VSB-Technical University of Ostrava, Tomas Bata University in Zlin, and University of Žilina. According to Table 10.13, China leads in the number of citing papers, followed closely by the USA. Table 10.14 indicates that the leading institutions in terms of citing papers are Texas A&M University, The Hong Kong Polytechnic University, and Tongji University.

Table 10.11 Countries with the greatest output of core papers on “modeling and enhancing resilience in urban physical-information-social systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	14	46.67	782	55.86	2019.1
2	China	10	33.33	442	44.20	2019.7
3	Canada	5	16.67	180	36.00	2019.2
4	Czech	3	10.00	180	60.00	2019.0
5	Slovakia	2	6.67	145	72.50	2018.5
6	Australia	2	6.67	111	55.50	2018.5
7	Germany	1	3.33	41	41.00	2023.0
8	Singapore	1	3.33	41	41.00	2023.0
9	India	1	3.33	33	33.00	2021.0
10	Norway	1	3.33	31	31.00	2020.0

Table 10.12 Institutions with the greatest output of core papers on “modeling and enhancing resilience in urban physical-information-social systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	The University of Hong Kong	4	13.33	196	49.00	2019.5
2	Mississippi State University	3	10.00	250	83.33	2019.3
3	VSB-Technical University of Ostrava	3	10.00	180	60.00	2019.0
4	Shanghai University of Finance and Economics	3	10.00	121	40.33	2018.7
5	The University of Southern Mississippi	2	6.67	189	94.50	2019.0
6	Tomas Bata University in Zlin	2	6.67	145	72.50	2018.5
7	University of Žilina	2	6.67	145	72.50	2018.5
8	South China University of Technology	2	6.67	91	45.50	2019.5
9	Purdue University	2	6.67	86	43.00	2020.0
10	The University of Western Ontario	2	6.67	82	41.00	2018.5

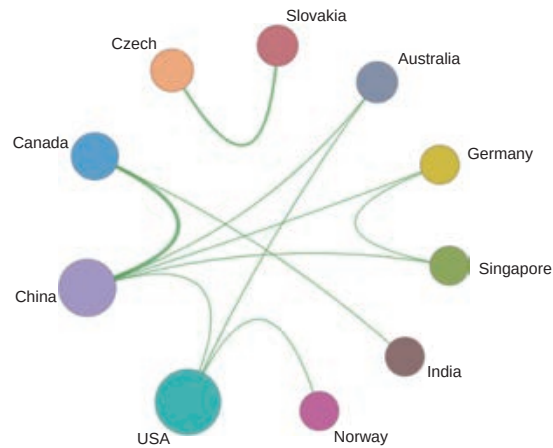


Figure 10.7 Collaboration network among major countries in the engineering research front of “modeling and enhancing resilience in urban physical-information-social systems”

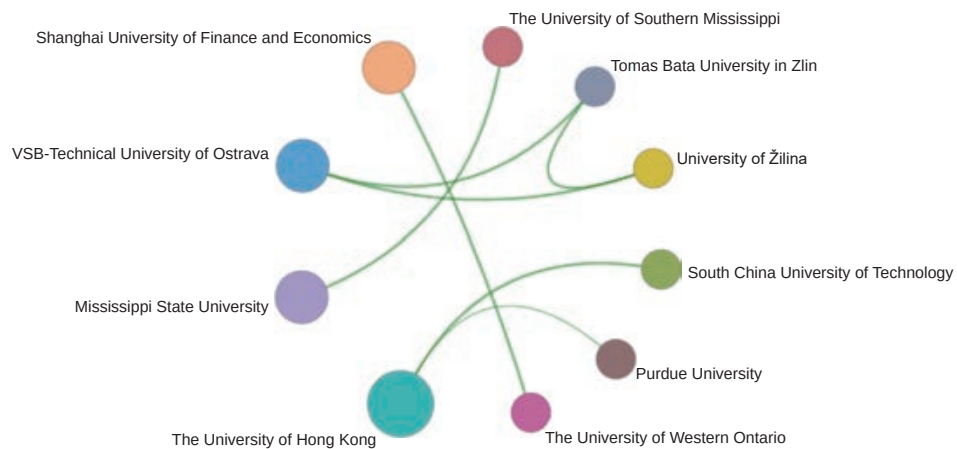


Figure 10.8 Collaboration network among major institutions in the engineering research front of “modeling and enhancing resilience in urban physical-information-social systems”

Figure 10.9 outlines the roadmap of “modeling and enhancing resilience in urban physical-information-social systems”. The objective of this research should be to create cross-dimensional and cross-system urban models. This can be facilitated through demand analysis and the implementation of key enabling technologies, including big data, machine learning, and artificial intelligence. Efforts should concentrate on enhancing the generalization capabilities of system modeling, formulating resilience assessment methodologies for complex risk scenarios, and optimizing resource allocation.

Table 10.13 Countries with the greatest output of citing papers on “modeling and enhancing resilience in urban physical-information-social systems”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	410	31.76	2022.1
2	USA	400	30.98	2021.7
3	UK	91	7.05	2021.8
4	Canada	72	5.58	2021.6
5	Iran	60	4.65	2021.8
6	Australia	51	3.95	2021.9
7	Italy	51	3.95	2021.5
8	India	46	3.56	2021.9
9	Germany	43	3.33	2021.7
10	Netherlands	36	2.79	2021.5

Table 10.14 Institutions with the greatest output of citing papers on “modeling and enhancing resilience in urban physical-information-social systems”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Texas A&M University	40	14.65	2021.3
2	The Hong Kong Polytechnic University	32	11.72	2022.2
3	Tongji University	30	10.99	2022.0
4	Tsinghua University	28	10.26	2021.5
5	Towson University	27	9.89	2021.8
6	University of Žilina	25	9.16	2020.8
7	Beijing Jiaotong University	20	7.33	2022.2
8	Guangzhou University	19	6.96	2023.0
9	Southeast University	18	6.59	2021.9
10	Arizona State University	17	6.23	2021.2

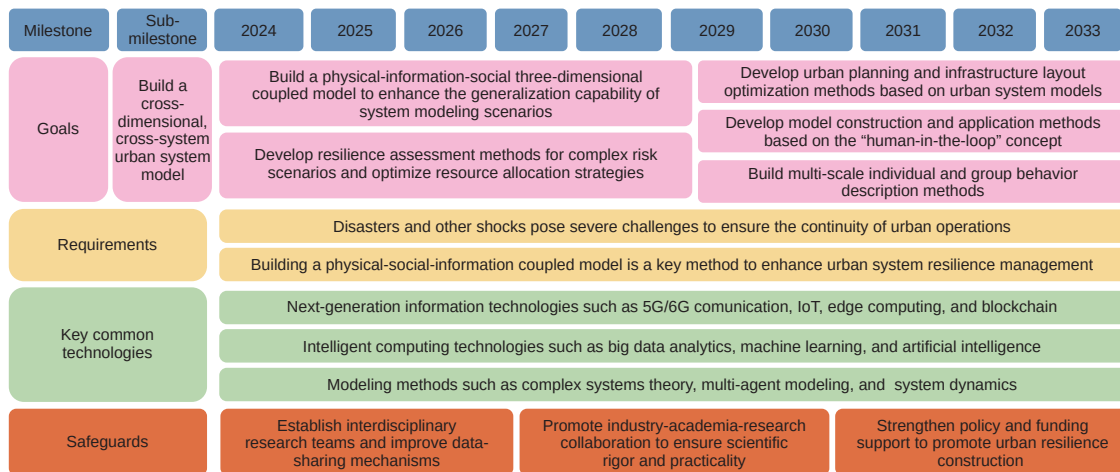


Figure 10.9 Roadmap of the engineering research front of "modeling and enhancing resilience in urban physical-information-social systems"

10.1.2.4 Comprehensive optimization and evaluation of green energy systems

Key research directions in the "comprehensive optimization and evaluation of green energy systems" include the refined modeling of electric-heat-gas conversion facilities, the modeling of green hydrogen supply systems, and the multidimensional evaluation of comprehensive energy systems. Additional focal areas include the optimization and reliable operation of electric-heat-gas (hydrogen) systems, planning and facility configuration of multi-network coupling systems, as well as the design of market mechanisms for green energy and the promotion of sustainable development policies. Specifically:

(1) Electricity-heat-gas conversion facilities and their detailed modeling

This research explores the detailed modeling of production, conversion, storage, and consumption processes within multi-energy coupled systems comprising electricity, heat, and gas. The primary objective is to facilitate the coordinated operation of these three networks, enhance energy utilization efficiency, and minimize both energy supply costs and carbon emissions. Critical research topics include the modeling and integration of renewable energy technologies, including photovoltaics, wind energy, and biogas, as well as the collaborative modeling of the physical and economic characteristics of multi-energy coupled systems.

(2) Green hydrogen supply system modeling and multi-dimensional evaluation of integrated energy systems

This area highlights the detailed modeling of the green hydrogen supply chain and its effective application within integrated energy systems. Innovative technologies, such as proton exchange membranes (PEM) and solid oxide fuel cells, are examined to enhance the efficiency and cost-effectiveness of hydrogen production and utilization. Research topics include multi-dimensional evaluations of system efficiency, economic advantages, environmental impacts, social benefits, reliability, and flexibility, thereby reflecting the comprehensive performance of heterogeneous energy coupling and multi-stage interactions. By leveraging advancements in IoT, cloud computing, and AI, the precision of these evaluations is improved, promoting the optimization and enhancement of integrated energy systems and supporting global energy transitions, socio-economic development, and environmental sustainability.

(3) Optimized scheduling and reliable operation of electricity-heat-gas (hydrogen) systems

This research focuses on coordinating the operation of different energy forms [electricity, heat, and gas (hydrogen)] to improve flexibility, efficiency, and cost-effectiveness, especially with supply and demand uncertainties. Key areas include

modeling energy conversion facilities under fixed and variable conditions, optimizing scheduling for green energy systems, and assessing the impact of model differences on scheduling. It also examines coordinated operations over different time frames, the role of seasonal energy storage in maintaining low-carbon, secure, and economic systems, and optimizing scheduling for varying energy demands. To boost reliability and flexibility, the research uses AI, big data, and advanced optimization algorithms.

(4) Planning of multi-network coupled systems and facility allocation

This research places significant emphasis on the interconnection and modeling of multi-energy flows and multi-network systems, alongside the design of interactive mechanisms spanning multiple time scales, stakeholders, and stages. The overarching goal is to plan and allocate energy equipment, construction sites for networks, and capacities while balancing the objectives of low carbon emissions, safety, and economic efficiency. Key areas of exploration include determining the location and size of electricity-heat-gas energy conversion facilities based on technology, construction status, and stakeholder investments. It also involves planning the expansion of green energy systems by integrating energy, information, and transportation flows, as well as managing reliability amid uncertainties in renewable energy and multi-energy loads across different time frames. Additionally, the research focuses on risk assessment and resilience planning for regional electricity-heat-gas (hydrogen) systems.

(5) Green energy market mechanism design and sustainable development policy promotion

The research focuses on the design of trading mechanisms that involve multiple stakeholders and integrate green certificates, carbon emissions, and electricity markets. The goal is to achieve safety, efficiency, and clean, low-carbon development. Key research areas include: ① designing grid feed-in tariffs for renewable energy power plants that consider cost structures; ② developing peer-to-peer trading mechanisms utilizing energy blockchain technology; ③ exploring multi-stakeholder decision-making in green energy markets characterized by limited rationality; ④ analyzing the interconnections between green certificates, carbon emissions, and electricity markets; ⑤ formulating green credit policies to promote clean energy planning, technological upgrades, and large-scale integration. Furthermore, the development of policy simulation platforms to assess the impact of different policy combinations on the growth of green energy systems is a central focus.

In the front of “comprehensive optimization and evaluation of green energy systems”, the top three countries in terms of core paper output are China, Iran, and Denmark (Table 10.15), with leading institutions being Aalborg University, University of Tehran, and Shanghai Jiao Tong University (Table 10.16). The international collaboration network (Figure 10.10) indicates that Denmark demonstrates strong cooperation with other countries. Regarding institutional collaboration (Figure 10.11), Aalborg University,

Table 10.15 Countries with the greatest output of core papers on “comprehensive optimization and evaluation of green energy systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	5	38.46	163	32.60	2019.6
2	Iran	3	23.08	44	14.67	2022.7
3	Denmark	2	15.38	108	54.00	2021.0
4	UK	2	15.38	84	42.00	2021.5
5	Republic of Korea	2	15.38	82	41.00	2022.0
6	India	1	7.69	64	64.00	2020.0
7	Singapore	1	7.69	55	55.00	2018.0
8	Saudi Arabia	1	7.69	44	44.00	2022.0
9	Tunisia	1	7.69	44	44.00	2022.0
10	United Arab Emirates	1	7.69	44	44.00	2022.0

Indian Institute of Technology (BHU) Varanasi, National Institute of Technology Patna, King Abdulaziz University, and Islamic Azad University maintain close partnerships. According to Table 10.17, China ranks first for the number of citing papers, with India following closely. Table 10.18 illustrates that the top three institutions with the highest number of citing papers are Islamic Azad University, Korea Institute of Industrial Technology, and Yonsei University.

Figure 10.12 shows the roadmap of “comprehensive optimization and evaluation of green energy systems”. The future development of this frontier field will concentrate on several key areas: ① detailed modeling of electricity-heat-gas (hydrogen) conversion facilities within green energy systems; ② multi-dimensional evaluation of green hydrogen production and integrated energy systems; ③ optimized scheduling and reliable operation of electricity-heat-gas (hydrogen) coupling; ④ planning of multi-network coupled systems and facility allocation; ⑤ designing market mechanisms and promoting sustainable development policies. Development trends suggest that, as multi-energy coupling technologies and optimization strategies advance, the modeling of multi-energy systems will become more refined and precise, resulting in smarter and more efficient energy system operations. Fully leveraging historical data within green energy systems to facilitate intelligent, reliable, low-carbon, and cost-effective energy operations will also represent a critical focus in the evolution of green energy systems.

Table 10.16 Institutions with the greatest output of core papers on “comprehensive optimization and evaluation of green energy systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Aalborg University	2	15.38	108	54.00	2021.0
2	University of Tehran	2	15.38	0	0.00	2023.0
3	Shanghai Jiao Tong University	1	7.69	74	74.00	2020.0
4	The University of Edinburgh	1	7.69	74	74.00	2020.0
5	Indian Institute of Technology (BHU) Varanasi	1	7.69	64	64.00	2020.0
6	National Institute of Technology Patna	1	7.69	64	64.00	2020.0
7	Beihang University	1	7.69	55	55.00	2018.0
8	National University of Singapore	1	7.69	55	55.00	2018.0
9	Islamic Azad University	1	7.69	44	44.00	2022.0
10	King Abdulaziz University	1	7.69	44	44.00	2022.0

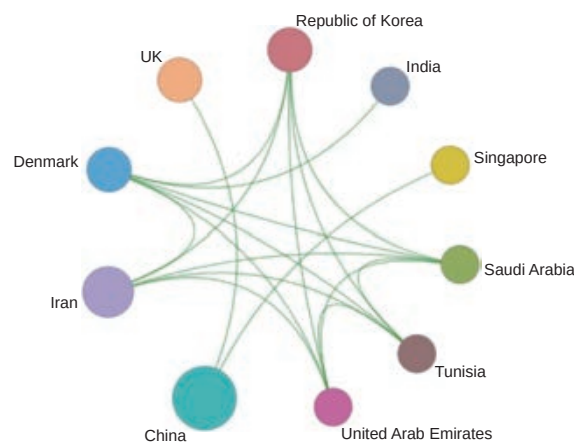


Figure 10.10 Collaboration network among major countries in the engineering research front of “comprehensive optimization and evaluation of green energy systems”

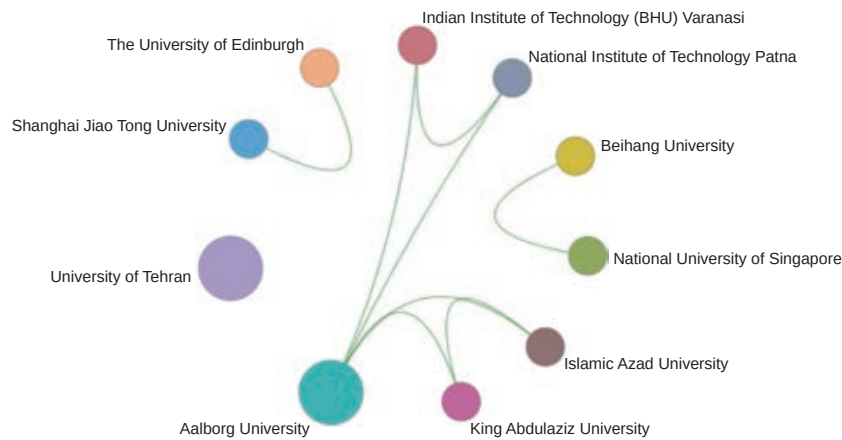


Figure 10.11 Collaboration network among major institutions in the research front of “comprehensive optimization and evaluation of green energy systems”

Table 10.17 Countries with the greatest output of citing papers on “comprehensive optimization and evaluation of green energy systems”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	130	38.01	2022.1
2	India	33	9.65	2022.1
3	Republic of Korea	33	9.65	2022.7
4	Iran	32	9.36	2022.7
5	USA	22	6.43	2022.1
6	UK	21	6.14	2022.5
7	Italy	19	5.56	2021.9
8	Australia	16	4.68	2021.4
9	Denmark	13	3.80	2021.9
10	Saudi Arabia	12	3.51	2022.2

Table 10.18 Institutions with the greatest output of citing papers on “comprehensive optimization and evaluation of green energy systems”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Islamic Azad University	13	12.26	2022.6
2	Korea Institute of Industrial Technology	13	12.26	2022.5
3	Yonsei University	13	12.26	2022.8
4	Aalborg University	12	11.32	2021.8
5	University of Tehran	9	8.49	2022.6
6	Yeungnam University	9	8.49	2023.0
7	Southeast University	8	7.55	2022.0
8	University of Sharjah	8	7.55	2022.5
9	Xi'an Jiaotong University	8	7.55	2022.8
10	Chongqing University	7	6.60	2021.7

Milestone	Sub-milestone	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Goals	Low carbon	Clean energy technologies such as photovoltaics, wind turbines, and green hydrogen						Pilot zero-carbon industrial parks				
	Efficiency	Autonomous coordinated management technology for multiple power resources				Electricity-heat-gas (hydrogen) multi-energy coupling technology				Energy storage and transportation technology		
	Intelligence	Intelligent scheduling technology						AI-based fault detection and self-healing technology				
Requirements		Full lifecycle modeling and multi-dimensional evaluation of green energy systems				Multi-objective planning and optimized scheduling of system operations				Market mechanism design and promotion of sustainable development policies		
Key directions	Detailed modeling of green energy systems and key conversion equipment	Detailed modeling of renewable energy systems such as photovoltaics, wind, and biogas			Dynamic modeling of electricity-heat-gas (hydrogen) multi-energy coupling systems			Hierarchical modeling platform design for equipment and system layers		Data-driven modeling based on big data and machine learning technologies		
		Optimization of core hydrogen production technologies like PE and SOE			Optimization of efficient energy storage and transmission technologies in multi-energy coupling systems			Study of diverse application scenarios of green hydrogen in different multi-energy coupling systems		Optimization of production, storage, and application strategies for green hydrogen in multi-energy coupling systems		
	Multi-dimensional lifecycle evaluation of electricity-hydrogen coupling systems	Multi-dimensional performance evaluation indicators for distributed electricity-hydrogen coupling systems				Comprehensive performance evaluation of electricity-hydrogen coupling systems				Optimization of energy structure and operating strategies of the system		
		Full lifecycle data processing of distributed electricity-hydrogen coupling systems			Construction of lifecycle evaluation models for electricity-hydrogen coupling systems		Analysis of key factors affecting the economic efficiency of electricity-hydrogen coupling systems		Optimization plan for electricity hydrogen coupling systems environmentally friendly and economically efficient goals			
	Optimization scheduling and reliable operation of green energy systems	Coupling of different energy forms			Modeling of source-load uncertainty on both sides			Fixed and variable condition modeling of conversion facilities		Optimization scheduling of green energy systems		
		Analysis of the impact of model discrepancies on scheduling			Coordinated operation of green energy systems on multiple timescales			Analysis of the impact of seasonal energy storage on the low-carbon, safe, and economic value of the system		System scheduling optimization under differentiated demand response for multi-energy loads		
	Planning of multi-network coupled systems and facility allocation	Modeling of multi-energy flow and multi-network integrated connection patterns			Design of multi-timescale, multi-entity, multi-phase interaction mechanisms			Planning and allocation of locations and capacities for equipment and network construction		Expansion planning of systems integrating energy flow, information flow, and traffic flow		
		Siting and sizing of electricity-heat-gas energy conversion equipment			Reliability planning considering source-load uncertainty			Risk measurement for the operation of green energy supply systems		Resilience enhancement planning for systems under extreme disaster events		
	Policy and market mechanism design and promotion for green energy systems	Analysis of existing green energy market mechanisms and policy frameworks			Research on market mechanisms incentivizing green energy production and consumption			Construction of a policy simulation platform considering the impact of different policy combinations on green energy system development		Formulation and promotion of green energy policies		
Key technologies	Equipment layer	Efficient photovoltaic systems				Advanced wind power generation				Efficient electrolysis and fuel cells		
	System layer	Multi-energy coupled energy management systems				Green energy market mechanisms				Green energy policy simulation platform		
	Technical support layer	Intelligent scheduling algorithms and optimization technologies				Energy blockchain technology				Automation control and fault self-healing technology		

Figure 10.12 Roadmap of the engineering research front of “comprehensive optimization and evaluation of green energy systems”

10.2 Engineering development fronts

10.2.1 Trends in the Top 10 engineering development fronts

In the field of engineering management, the global Top 10 engineering development fronts this year are “data and model-driven intelligent mathematical programming algorithms”, “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”, “cloud-edge-end data collaborative management platform for engineering construction”, “emotionally and intellectually capable digital humans for service innovation”, “key technologies for urban ecological risk early warning, control, and resilience enhancement”, “urban streetscape perception technology and spatial feature identification methods”, “research on big data coupling, assimilation, and intelligent perception for atmospheric environment prediction”,

“privacy computing methods and systems in environmental intelligence”, “edge-cloud collaborative evolution of large and small models”, and “key technologies for multidimensional state perception and optimized scheduling in complex manufacturing systems”. Citations to seminal articles pertinent to these topics can be found in Tables 10.19 and 10.20. Among these domains,

Table 10.19 Top 10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Data and model-driven intelligent mathematical programming algorithms	43	247	5.74	2021.1
2	Development of large model technologies and scenario libraries for closed-loop data in autonomous driving	54	885	16.39	2022.4
3	Cloud-edge-end data collaborative management platform for engineering construction	42	67	1.60	2022.4
4	Emotionally and intellectually capable digital humans for service innovation	54	57	1.06	2022.2
5	Key technologies for urban ecological risk early warning, control, and resilience enhancement	81	81	1.00	2022.2
6	Urban streetscape perception technology and spatial feature identification methods	32	190	5.94	2021.6
7	Research on big data coupling, assimilation, and intelligent perception for atmospheric environment prediction	95	140	1.47	2021.8
8	Privacy computing methods and systems in environmental intelligence	33	180	5.45	2022.3
9	Edge-cloud collaborative evolution of large and small models	18	51	2.83	2022.4
10	Key technologies for multidimensional state perception and optimized scheduling in complex manufacturing systems	18	40	2.22	2021.9

Table 10.20 Annual number of core patents published for the Top 10 engineering development fronts in engineering management

No.	Engineering development front	2018	2019	2020	2021	2022	2023
1	Data and model-driven intelligent mathematical programming algorithms	4	5	7	4	14	9
2	Development of large model technologies and scenario libraries for closed-loop data in autonomous driving	0	0	0	7	16	31
3	Cloud-edge-end data collaborative management platform for engineering construction	2	1	2	1	2	34
4	Emotionally and intellectually capable digital humans for service innovation	2	0	1	6	16	29
5	Key technologies for urban ecological risk early warning, control, and resilience enhancement	0	1	4	12	23	41
6	Urban streetscape perception technology and spatial feature identification methods	2	1	5	4	8	12
7	Research on big data coupling, assimilation, and intelligent perception for atmospheric environment prediction	6	3	10	10	23	43
8	Privacy computing methods and systems in environmental intelligence	0	0	1	6	9	17
9	Edge-cloud collaborative evolution of large and small models	0	0	0	2	6	10
10	Key technologies for multidimensional state perception and optimized scheduling in complex manufacturing systems	0	1	2	2	6	7

particular attention is accorded to “data and model-driven intelligent mathematical programming algorithms”, “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”, “cloud-edge-end data collaborative management platform for engineering construction”, and “emotionally and intellectually capable digital humans for service innovation”. Succeeding sections will offer a robust analysis of their extant developmental trajectories and prospective orientations.

(1) Data and model-driven intelligent mathematical programming algorithms

In the field of management science, traditional decision-making methodologies often treat models and data as separate entities, leading to potential misalignments between optimization objectives and actual decision goals. This misalignment can compromise both the effectiveness and quality of decisions. To overcome this limitation, data and model-driven intelligent mathematical programming algorithms have been developed. The fundamental principle of this approach is the seamless integration of data analysis with mathematical modeling. This integration enables the adjustment and optimization of model parameters throughout the decision-making process, allowing for better adaptation to dynamic environmental conditions. This method enhances not only decision accuracy and efficiency but also the adaptability and flexibility of the model.

Key research directions in this area include online learning and optimization, wherein the model is continuously updated in real-time decision-making to incorporate new data inputs; interdisciplinary approaches that merge machine learning techniques with operations research principles to address complex and nonlinear decision problems; and enhancements to the algorithm's adaptability to specific data distributions and real-world application scenarios. With the rapid advancement of big data and AI technologies, data and model-driven intelligent mathematical programming algorithms are attracting growing interest in both academic and industrial sectors.

Future development trends will emphasize the enhancement of real-time processing and automation capabilities of the algorithms, as well as the exploration of multimodal data processing and deep learning technologies to bolster the decision model's self-learning and adaptive capabilities. Furthermore, these algorithms are anticipated to find extensive application in industries that necessitate rapid and precise decision-making, such as power system optimization and cloud computing resource scheduling, thereby delivering innovative solutions and significant efficiency improvements in these fields.

(2) Development of large model technologies and scenario libraries for closed-loop data in autonomous driving

Autonomous vehicles (AVs) have attracted significant attention in recent years due to their transformative potential in improving traffic safety and mobility. A crucial aspect of developing and deploying AVs involves generating diverse scenarios to rigorously test and evaluate the vehicle's driving intelligence—its capacity to operate safely and efficiently without human intervention. The emergence and advancement of foundational models, such as large language models (LLMs) and vision-language models (VLMs), highlight their remarkable capabilities in understanding complex situations, exhibiting emergent behaviors, and generating content. These advancements open new avenues for creating scenarios relevant to autonomous driving. By leveraging extensive datasets comprising text and video, these large models can produce complex, detailed, and high-fidelity driving scenarios and adapt them dynamically based on varying input conditions and feedback, significantly enhancing the flexibility and comprehensiveness of scenario generation and testing.

Current prevalent methods for testing AVs employ an agent-environment framework, integrating software simulations, closed-track testing, and on-road testing. The fundamental premise is to evaluate the AVs' intelligence within real-world driving environments, monitor its performance, and statistically compare it to that of human drivers. However, this testing faces challenges across three dimensions. First, AVs' intelligence primarily relies on statistical or artificial intelligence algorithms, which restrict the applicability of traditional logic-based software verification and validation techniques. Second, the driving environment is often complex and stochastic. Capturing its full complexity and variability can be challenging, as high-dimensional environmental variables may lead to the “curse of dimensionality”. Moreover, the inherent randomness of these environments renders traditional absolute safety formal methods less effective. Third, the infrequency of safety-critical events during driving intelligence tests leads to inefficient testing processes.

Consequently, the central challenge in evaluating AVs' safety performance lies in constructing intelligent scenarios that effectively and efficiently assess driving intelligence while managing high dimensionality and the infrequency of critical events. Current research is concentrated on scenario modeling and simulation, critical case generation, and scenario testing analysis. Scenario modeling and simulation focus on creating realistic driving environments for testing, while the generation of critical cases aims to validate system safety in extreme and rare scenarios. Data collection and analysis involve a thorough examination of test data to assess system performance and identify potential issues.

(3) Cloud-edge-end data collaborative management platform for engineering construction

The engineering construction process is characterized by its large scale, extended duration, and the engagement of multiple stakeholders. Nevertheless, the engineering data generated throughout this process has not been fully leveraged in previous studies due to its multi-source, heterogeneous nature, time sensitivity, and inherent noise. With the continuous evolution of innovative smart construction models and the deep integration of advanced intelligent technologies into modern industrialized construction practices, the substantial amounts of data produced during the engineering process are now being collected, analyzed, and processed in real time, thereby unlocking their potential value. This advancement has facilitated the emergence of a cloud-edge-end data collaborative management platform for engineering construction.

By deeply integrating technologies such as cloud computing, edge computing, IoT, and blockchain, this platform enables efficient collaboration and unified management of data throughout the construction process. This ultimately enhances decision-making across various aspects, including project progress, resource allocation, and quality risk management. Current research efforts are concentrated on enhancing the real-time and comprehensive nature of data collection, ensuring the linkage and security of multi-party data collaboration and sharing across cloud-edge-end platforms, improving the accuracy and efficiency of analyzing and processing multi-source heterogeneous data, and bolstering the stability and reliability of the platform itself.

Key research areas include the integration of data collection, transmission, and analysis; the optimization of computational resources and task scheduling on the cloud-edge-end platform; and the protection of data privacy and security in collaborative data sharing. However, there remains significant room for improvement in the platform's efficiency in data collaboration, the accuracy of data analysis, and the security of data sharing practices. Therefore, future research is anticipated to concentrate on technologies for managing cloud-edge-end nodes, collaboration techniques between edge and cloud, cloud-edge data analysis and algorithm optimization, task offloading strategies for cloud-edge computing, and the integration of cloud-edge-end platforms with blockchain technology.

(4) Emotionally and intellectually capable digital humans for service innovation

"Emotionally and intellectually capable digital humans for service innovation" refers to virtual characters that integrate digital human technology with artificial intelligence, specifically engineered to meet the needs of the service sector. These digital humans not only imitate human appearance and movement but also facilitate natural language communication and emotional expression, offering users a more immersive and authentic interaction experience. Typically, such digital beings exhibit a high degree of anthropomorphism, including facial expressions, linguistic communication, emotional recognition, and feedback capabilities.

The primary research directions within this field include:

- 1) 3D human modeling and animation technology: employing multi-view and multi-light-source precise data capture or artificial intelligence techniques to reconstruct high-quality 3D human models from 2D images or videos, effectively reproducing natural movement and facial expressions.
- 2) Multimodal interaction: merging various interaction approaches, such as voice, vision, and text, to enhance engagement between the digital human and real users, thus improving the naturalness and intelligence of the interaction.
- 3) Affective computing: investigating human emotional models and leveraging AI to enable digital humans to recognize and simulate human emotions, facilitating authentic emotional expression during exchanges.

4) Autonomous learning and decision-making: in specific service domains, employing data perception and machine learning algorithms allows digital humans to learn independently and make decisions, thereby enhancing their adaptability and capacity to deliver personalized services.

As new applications arise and technology progresses, emotionally and intellectually capable digital humans will increasingly contribute to service innovation, providing more personalized and intelligent service experiences. Nonetheless, challenges persist related to realism, personalization, interaction, ethics, and privacy, necessitating collaborative efforts between academia and industry to address these issues.

(5) Key technologies for urban ecological risk early warning, control, and resilience enhancement

Cities are central units where socio-economic activities and environmental resources closely interact. Precision and modern urban governance are critical strategic needs for China. Addressing challenges related to early warning and control of urban ecological risks, alongside enhancing urban ecological resilience, is essential to support the national “comprehensive emergency” strategy and ensure urban ecological security. Current advancements in this field include:

- 1) Intelligent perception and early warning model for urban environmental pollution risks: This model manages complex pollution involving multiple pollutants, scales, and media. It leverages precise detection, intelligent linked sensing, and integrated sky-space-ground remote sensing technologies for ecological and environmental monitoring, enabling automated perception, risk assessment, and early warning of urban environmental risks.
- 2) Urban extreme climate disaster and secondary risk assessment system: This system develops data assimilation and hard-linked model technologies to create cross-domain risk assessment models at the urban scale. It integrates climate, hydrology, ecology, environment, health, and industry and includes dynamic simulation of disaster scenarios for extreme climate events and their impacts across multiple domains.
- 3) Key technologies and decision-making platform for enhancing urban ecological resilience: Focusing on critical areas such as environmental health, water-energy-food supply chains, vulnerable ecosystems, and critical infrastructure, this initiative builds a technology repository and decision-making platform. These tools are driven by multi-risk factors, including pollution, resource shortages, and climate events, to enhance system resilience.

Future research will focus on several key areas:

- 1) Behavior-driven risk control: This involves developing intelligent large-scale models for simulating and controlling risk scenarios, improving early warning and emergency response to severe pollution risks, environmental violations, and public sentiment on environmental issues.
- 2) Process safety: This aims to enhance the precision and intelligence of evaluating cascading and coupled ecological risks within urban systems.
- 3) Decision support for risk adaptation: This platform will optimize cost-benefit analysis, ensure robustness under complex scenarios, and maximize collaborative benefits across multiple dimensions of urban risk management.

(6) Urban streetscape perception technology and spatial feature identification methods

Urban streetscapes are an influential aspect of understanding people's perceptions and behaviors. Over the past fifty years, urban designers and scholars have studied how people perceive the variety of streetscape designs, ultimately improving the urban experience. An examination of urban perception, interpreted here as the understanding of the urban environment by people and groups, is part of this examination. Urban visual perception can be considered one branch of urban perception involving how the visual items influence perception. In the past, inquiry into urban visual perception showed it gives valid insight into subjective human events through a human perspective.

Recent advances in computer vision and easier access to urban visual data, like street view images, satellite imagery, video, virtual

reality, and aerial images, give researchers more ways to study urban environments. These tools help broaden investigations and create new opportunities to measure how people perceive cities, expanding the field of research. The incorporation of computer vision to extract attributes on a street-level has become the norm and encourages researchers to correlate direct or indirect studies with urban streetscapes town studies. Utilizing methods with big datasets such as street view images and computer vision models, can provide research with better understanding how people perceive urban environments.

Equity across statistical sample will be enriched by continuing to contemporize a diverse array in urban streetscape scenes and attributes. In order to take the burden off of data collection and participant engagement on behalf of the researcher, civic data sources to provide an open source platform for continued evaluation (where individuals can individually rate images) can make urban perception research more equitable. Additionally, gamifying the collection of perception data from engaged individuals provides a creative and innovative research method. Moreover, gamifying the collection of perception data offers an innovative approach, potentially engaging a broader audience in urban studies.

[\(7\) Research on big data coupling, assimilation, and intelligent perception for atmospheric environment prediction](#)

The integration of big data, AI, blockchain, and other digital technologies in the domain of air pollution control has paved the way for innovative methods of atmospheric environmental monitoring and forecasting. This research aims to develop a comprehensive quality control and assimilation analysis system specifically designed for conventional pollutants, aerosol components, photochemical observations, and high-resolution simulations. The system generates an integrated assimilated dataset that enhances the precision of air pollution management. By employing rapid data fusion, automated sensing analysis, AI-driven analytics, and seamless data sharing within the domain of environmental big data, this study merges atmospheric monitoring data with pollutant sources, meteorological conditions, and simulation data, enabling sophisticated coupled analysis. This integration facilitates the prompt detection of air pollution incidents, identifies severe pollution processes, and traces pollution sources, ultimately leading to the formulation of effective control strategies. To overcome prevalent challenges associated with the application of big data and AI in atmospheric environments (such as data bottlenecks, limitations in simulation performance, and the management of complex systems), this research presents an innovative simulation system for atmospheric environments. This system leverages AI and dynamic hybrid mechanisms to predict the evolution of sudden air pollution events, enabling seamless AI-driven forecasting and optimized control solutions. It establishes a technology framework that seamlessly integrates AI and big data for the simulation, prediction, and management of atmospheric conditions. Moreover, a new information system has been developed to facilitate environmental big data coupling, assimilation, and intelligent sensing, supported by robust scientific infrastructure and high-performance computing platforms. Blockchain technology will enhance the sharing of research findings, promoting the application of shared data and technologies. Looking ahead, advancements in big data coupling, assimilation, and intelligent prediction technologies for atmospheric environments are poised to transform research and management paradigms in environmental science, contributing to the vision of a “Beautiful China” and enhancing global environmental governance.

[\(8\) Privacy computing methods and systems in environmental intelligence](#)

Privacy computing includes a set of technologies designed to safeguard data privacy during processing activities. Its primary goal is to facilitate effective data utilization without compromising sensitive information. The predominant privacy computing methods and systems can be categorized into three main types: cryptography-based secure multi-party computation (SMPC), federated learning technologies that integrate privacy protection with distributed machine learning, and trusted execution environment (TEE) technology, which relies on secure hardware. Although privacy computing technologies are advancing quickly, they face challenges in complex environments and large-scale devices. These include inefficient learning and communication, high resource demands for privacy protection, and vulnerability to attacks that can lead to data breaches. For example, while federated learning is ideally suited for high-performance and scalable modeling scenarios, it is vulnerable to attacks such as gradient inversion, which can result in privacy leaks, and it lacks general computational capabilities. Conversely, SMPC provides enhanced security but involves complex computational logic and incurs significant communication costs. TEE technology can accommodate more complex computational demands yet is heavily reliant on specialized hardware, which constrains its broader applicability.

Consequently, when considering the application needs of privacy computing within environmental intelligence, it becomes evident that no single technology can “cover all bases”. The future of privacy computing must involve a synthesis of various techniques tailored to the specific characteristics of application scenarios. This approach will ensure the security and privacy of raw data while facilitating its computation and analysis. Additionally, in practical implementations, privacy computing should be integrated with data governance technologies (such as blockchain and smart contracts) to establish a robust trust mechanism for “digital identity, algorithms, computation, and regulation”. This integration will further enhance the development of a reliable framework for data ownership, pricing, and trading.

(9) Edge-cloud collaborative evolution of large and small models

“Edge-cloud collaborative evolution of large and small models” represents a significant frontier in AI and distributed computing. This development addresses the imbalance between the performance enhancements offered by large-scale pre-trained models and their growing energy consumption, which poses limitations on the expansion of model parameters. It also highlights the challenges associated with deploying intelligent applications on edge devices, such as mobile technology. Moving beyond the era of large models, the innovation trajectory is transitioning from a competition centered on cloud-based models to a hybrid approach that synergizes the robust inference capabilities of large cloud models with the low-latency benefits of smaller edge models. This strategy is designed to enhance overall system intelligence while improving resource efficiency, thereby facilitating broader adoption of AI technologies.

Research in this area is concentrated in countries such as China, the USA, Europe, and India. Leading academic institutions and enterprises driving innovation include Shanghai Jiao Tong University, Zhejiang University, Tsinghua University, Peking University, MIT, UC Berkeley, Alibaba, Huawei, Google, OpenAI, Microsoft, and Apple. These organizations contribute significantly not only to theoretical advancements in algorithms but also to their practical applications, including recommendation systems, natural language understanding, visual object detection and recognition, and autonomous driving. The research is characterized by deep collaborations between academia and industry.

Current investigations focus on model dimensionality reduction and compression, edge-cloud homomorphic model aggregation, privacy protection and security, and system platforms. Future research directions include flexible decomposition of complex models, personalized enhancement of lightweight models, and collaborative generalization of heterogeneous models. This technology is anticipated to find widespread application across various intelligent terminals and IoT devices, driving the digital and intelligent transformation of industries such as smart retail, smart cities, smart homes, intelligent manufacturing, smart education, and smart healthcare.

(10) Key technologies for multidimensional state perception and optimized scheduling in complex manufacturing systems

Complex manufacturing systems are marked by heterogeneous equipment, complex processes, and significant interdependencies. Multidimensional state perception within these systems involves utilizing various sensors and advanced data processing techniques to monitor and analyze vast amounts of multi-source, heterogeneous, low-quality, and high-noise industrial multimodal data in real-time. This data is related to equipment status, the production environment, and process flows within the system. By perceiving the multidimensional state information of the manufacturing system and integrating it with intelligent scheduling algorithms, dynamic adjustments can be made to production processes, including job scheduling and transportation routes. This approach facilitates the optimization of resource allocation—including labor, equipment, and transport capacity—aimed at enhancing production efficiency and reducing energy consumption.

As technologies like the industrial internet, edge computing, and big data evolve, their use has grown beyond basic tasks like data collection, processing, production control, and equipment management. They now play a role in production scheduling and optimization, using real-time data to inform decision-making. This technology enables multidimensional data perception and intelligent scheduling across multiple stages of the production system, allowing for effective management and control of complex manufacturing systems.

When achieving intelligent perception in manufacturing systems proves to be challenging, it is essential to establish a collaborative manufacturing cloud control system that integrates terminal devices, edge computing, and cloud computing. In scenarios where precise modeling of complex manufacturing systems is difficult, data-driven cross-domain manufacturing modeling becomes necessary. Furthermore, when traditional optimization methods fall short of addressing the dynamic operational needs of small-batch, multi-variety production, it is crucial to develop intelligent dynamic optimization scheduling strategies and approaches tailored for heterogeneous environments.

Consequently, the primary research directions focus on the comprehensive process of data sensing, processing, optimization, decision-making, and execution within manufacturing. This includes real-time intelligent sensing of multi-dimensional data regarding manufacturing terminal status, extraction of hidden knowledge from historical manufacturing big data, accurate cross-domain manufacturing data modeling, and intelligent dynamic optimization scheduling across heterogeneous scenarios. Additionally, the construction of cloud control systems, such as “cloud-network-edge-terminal”, is crucial. Future research in this field will involve multi-sensor data fusion, autonomous iteration of smart factory cloud control systems, and the integration of full-process data sensing, optimization, and scheduling for manufacturing systems based on large-scale industry models.

10.2.2 Interpretations for four key engineering development fronts

10.2.2.1 Data and model-driven intelligent mathematical programming algorithms

In traditional management research and practice, models and data are often treated as separate entities. Because the objectives of prediction and optimization may not fully align with actual decision-making goals, treating models and data independently can lead to suboptimal decisions. The focus of data and model-driven intelligent mathematical programming algorithms is to integrate the inherent patterns found in data with the characteristics of mathematical programming models, thereby facilitating a unified approach to intelligent decision-making. The programming model and algorithm establish the theoretical foundation for problem-solving, while data patterns significantly enhance algorithm performance across various application scenarios. Traditional mathematical programming models often serve as generalized abstractions of multiple practical situations, necessitating algorithm design that accounts for worst-case theoretical conditions to ensure solution stability across a range of problems. However, in practice, data related to certain types of issues often exhibit specific distributions or patterns. By recognizing and leveraging these data patterns, it is possible to address the overly abstract and conservative tendencies of conventional model and algorithm design. Recently, as more scenarios involve dynamic decision-making and data variability, data and model-driven intelligent mathematical programming algorithms have gained prominence in operations research and machine learning. This has resulted in significant advancements, including a suite of methods exemplified by online learning.

Online learning is a prominent mathematical programming approach that integrates data and models in a profound manner. Unlike the traditional offline optimization framework, where data modeling occurs prior to solving, online learning generates data concurrently with the optimization process. This methodology entails a trade-off, accepting a minor loss in optimality to enable the efficient execution of intelligent decisions. However, challenges such as non-stationary data and external disruptions present substantial obstacles to online learning and decision-making, as the learning objectives may evolve over time or provide strategic feedback. These factors complicate the maintenance of a balance between “exploration” and “exploitation” in online learning.

In practice, machine learning—which includes techniques such as deep learning and reinforcement learning—is frequently leveraged to extract patterns and features from data. This “data and model-driven” approach represents a convergence of machine learning and operations optimization. Bengio et al. (2021) identified several paradigms for integrating machine learning with optimization algorithms: using machine learning to predict optimal solutions, utilizing machine learning for the selection

of alternative algorithms and parameters, and embedding machine learning directly within optimization algorithms. These paradigms exhibit varying degrees of integration, ranging from shallow to deep, and have found extensive application in industrial sectors, including power system optimization and cloud computing resource scheduling.

Within the domain of “data and model-driven intelligent mathematical programming algorithms”, the top three countries in terms of patent production are China, the USA, and Japan (Table 10.21). Based on the collaboration network among major countries (Figure 10.13), there is evidenced cooperation between Republic of Korea and Poland. The primary institutions responsible for the generation of core patents include Kunming University of Science and Technology, Kunming Prospecting Design Institute of China Nonferrous Metals Industry Co., Ltd., State Grid Corporation of China, and Hitachi, Ltd. (Table 10.22). Notably, Kunming University of Science and Technology has established a collaboration with Kunming Prospecting Design Institute of China Nonferrous Metals Industry Co., Ltd. (Figure 10.14).

“Data and model-driven intelligent mathematical programming algorithms” represents an important development direction for bringing optimization theory into efficient practical applications. Future key research areas include:

- 1) Application expansion: As digitization progresses in various industries and data continues to accumulate, there is a need to

Table 10.21 Countries with the greatest output of core patents on “data and model-driven intelligent mathematical programming algorithms”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	36	83.72	201	81.38	5.58
2	USA	3	6.98	38	15.38	12.67
3	Japan	2	4.65	4	1.62	2.00
4	Republic of Korea	1	2.33	2	0.81	2.00
5	Poland	1	2.33	2	0.81	2.00
6	Russia	1	2.33	2	0.81	2.00

Table 10.22 Institutions with the greatest output of core patents on “data and model-driven intelligent mathematical programming algorithms”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Kunming University of Science and Technology	16	37.21	124	50.20	7.75
2	Kunming Prospecting Design Institute of China Nonferrous Metals Industry Co., Ltd.	9	20.93	12	4.86	1.33
3	State Grid Corporation of China	3	6.98	9	3.64	3.00
4	Hitachi, Ltd.	2	4.65	4	1.62	2.00
5	Electric Power Research Institute of Guangxi Power Grid Co., Ltd.	1	2.33	23	9.31	23.00
6	Zhejiang University	1	2.33	12	4.86	12.00
7	International Business Machines Corporation	1	2.33	10	4.05	10.00
8	Guangdong University of Technology	1	2.33	8	3.24	8.00
9	China Petroleum & Chemical Corporation	1	2.33	7	2.83	7.00
10	Tianjin University	1	2.33	6	2.43	6.00

provide data and model-driven mathematical programming solutions for more sectors based on existing data.

2) Technological innovation: Integrating the latest advancements in online learning and machine learning (e.g., multimodal large models) into industry practices.

3) Incorporating hardware drivers: Exploring the potential of emerging computing platforms such as GPUs and quantum computing to enhance mathematical programming algorithms on the foundation of data and model integration.

Figure 10.15 illustrates the roadmap for “data and model-driven intelligent mathematical programming algorithms”. This technology development plan is structured into three distinct phases, each addressing specific objectives and tasks. The first phase (2024–2026) aims to establish a robust theoretical foundation by creating a comprehensive framework for data and model-driven algorithms. The second phase (2026–2028) will concentrate on achieving breakthroughs in core technologies, particularly through the integration of intelligent algorithms with emerging technologies. The third phase (2028 and beyond) will emphasize innovative industrial practices, applying the developed theories and technologies to complex systems and high-throughput platforms. Through the systematic development of the algorithm framework, evaluation systems, and engineering management methodologies, this plan aspires to enhance the overall maturity and practical application of the technology.

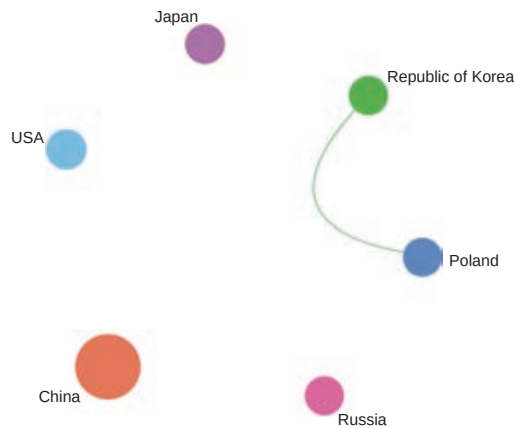


Figure 10.13 Collaboration network among major countries in the engineering development front of “data and model-driven intelligent mathematical programming algorithms”

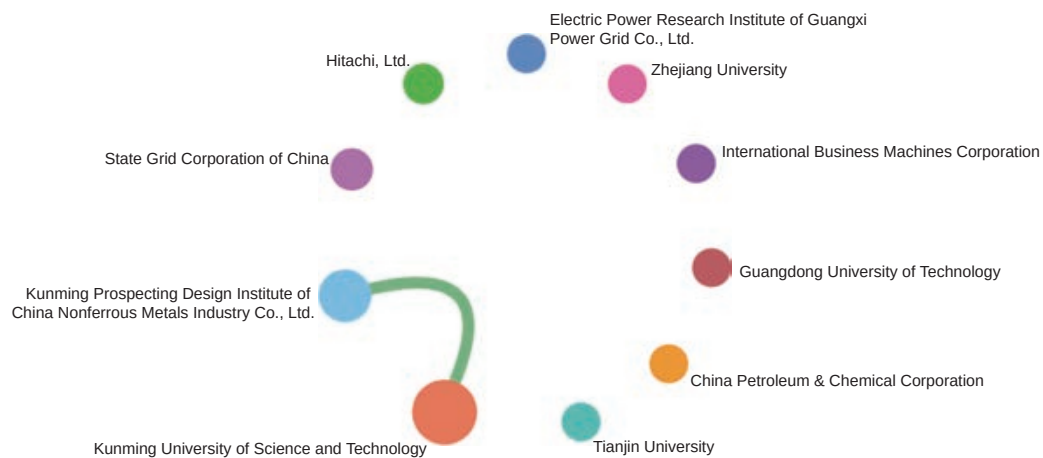


Figure 10.14 Collaboration network among major institutions in the engineering development front of “data and model-driven intelligent mathematical programming algorithms”

Milestone	2024	2025	2026	2027	2028	2029	2030
Goals	Strengthening the theoretical foundation: The theoretical system of data and model driven algorithm is established		Breakthroughs in core technologies: The fusion of intelligent algorithms and emerging technologies		Industrial innovation practices: The theory and technology are applied to complex system and high throughput platform		
Key tasks	Theoretical framework for data and model-driven algorithms		Integrated algorithms for online learning and machine learning		Complex systems such as power dispatch, petroleum, and metallurgy		
	Technical framework for constructing data and model-driven algorithms		Learning techniques for non-stationary problems		High-throughput platforms like cloud computing and online advertising		
	Evaluation framework for data and prototype-driven systems		Intelligent algorithms driven by hardware-software integration		Engineering management methods driven by model and data integration		
	Maturity assessment of data and model-driven algorithms		Integration of emerging technologies such as quantum computing		Innovative theoretical paradigms driven by model and data integration		

Figure 10.15 Roadmap of the engineering development front of “data and model-driven intelligent mathematical programming algorithms”

10.2.2.2 Development of large model technologies and scenario libraries for closed-loop data in autonomous driving

One of the primary challenges in the development and deployment of AVs is the substantial economic and temporal costs associated with validating their safety in natural driving environments, primarily due to the infrequency of safety-critical events. Achieving high safety performance in AVs necessitates comprehensive data collection on safety-critical incidents, precise modeling and prediction of the behavior of surrounding road users, accurate learning and decision-making in safety-critical scenarios, and efficient verification and validation of the intelligent driving safety performance. Current autonomous driving systems continue to encounter significant obstacles in comprehending complex scenarios:

- 1) Sensor data fusion challenge: Autonomous vehicles typically rely on a range of sensors, including cameras and radar, to perceive their environment, resulting in the generation of diverse types of environmental data. However, ensuring the reliability and effectiveness of this data presents a challenge. Additionally, safety-critical perception tasks in AVs face more pronounced issues related to data imbalance compared to traditional scenarios. Current approaches, such as class rebalancing, data augmentation, and module enhancements, can only adequately address limited imbalance ratios.
- 2) Dynamic scenario prediction challenge: The behavior of humans and other vehicles on the road is inherently unpredictable, complicating the ability of rule-based and pre-defined scenario library methods to capture the intricacies of real-world dynamic scenarios. These methods often struggle to accurately simulate varying road conditions, erratic traffic behaviors, and complex environmental variables. Achieving precise predictions in such dynamic and complex environments necessitates not only detecting the positions and movement trajectories of objects but also interpreting traffic signals and human intentions.
- 3) Long-tail scenario prediction challenge: In practice, rare or extreme situations (e.g., sudden road obstacles, vehicle malfunctions, and pedestrian intrusions) occur infrequently within training datasets. This scarcity can result in significant estimation biases within current models, such as those based on deep learning, thereby compromising the effectiveness of scenario generation and testing in the context of autonomous driving.

Consequently, enhancing the generalization and reasoning capabilities of machine learning models to mitigate the issue of data scarcity, particularly without relying on extensive task-specific datasets, has emerged as a critical concern in the domain of autonomous driving scenario generation and testing. This evolution requires AI agents to develop both bottom-up (perception-driven) and top-down (cognition-driven) reasoning abilities to effectively bridge the information gaps that existing data cannot address.

In recent years, foundational models, such as LLMs and VLMs, have exhibited notable generalization and reasoning capabilities in natural

language processing and visual understanding. These advancements stem from leveraging techniques such as fully supervised fine-tuning, contextual learning, and chain of thought reasoning. Characterized by large-scale parameters and deep nonlinear structures, LLMs and VLMs are adept at accurately capturing underlying patterns and subtle differences within data. Additionally, these models show robust representation learning capabilities through pre-training and transfer learning, enabling them to effectively uncover rare category patterns within high-dimensional feature spaces. This functionality significantly enhances the prediction performance of low-frequency, safety-critical events within long-tail distributions. Current mainstream research directions include:

- 1) Adapting and optimizing large language models for autonomous driving scenario generation: Large models can facilitate the integration of multimodal data, such as various complex road conditions, weather scenarios, and pedestrian behaviors, thereby allowing LLMs to generate rare and dynamic driving scenarios. This process involves synthesizing existing autonomous driving datasets with rule-based libraries, enabling LLMs to produce natural language descriptions of these scenarios, which are subsequently transformed into predictive visual scene information (e.g., vehicle intentions, road conditions).
- 2) Developing scenario generation methods based on prompt learning: Prompt learning empowers models to generate efficient and accurate driving scenarios from simple natural language descriptions. By designing and optimizing prompts, large language models can be steered toward the generation of complex driving scenarios. The inherent flexibility of prompts ensures that the produced scenarios possess adequate diversity and complexity, reflecting a broad spectrum of potential driving environments. With context-awareness, the generated scenarios gain realism and logical coherence. By incorporating multimodal information, such as visuals and audio, alongside prompts, more comprehensive driving scenarios can be created. Moreover, techniques for automatic prompt generation can dynamically adjust prompts to tailor scenarios to specific requirements, thereby providing substantial support for scenario simulation, system testing, and model optimization.
- 3) Building a sustainable closed-loop data generation system: The scenario data generated by LLMs can be reintegrated into autonomous driving models to evaluate their performance and adjust the data generation strategy dynamically. For example, if the model exhibits subpar performance in a specific type of scenario, the system can produce more similar scenarios to improve the model's adaptability, thereby diversifying the scenarios and covering a wider range of driving conditions. This approach ensures that the generated data not only enhances the model's robustness but also specifically targets its deficiencies in certain situations.

Current research indicates that, within the domain of “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”, the USA, China, and Japan lead in the number of core patents, while China, the UK, and Israel rank highest in citations per patent (Table 10.23). In the collaboration network of key countries/regions producing core patents (Figure 10.16), China demonstrates strong partnerships with the USA and Japan. J. Zico Kotler's team is focused on the intersection of machine learning and control. They propose a closed-loop, data-driven control framework that employs reinforcement learning and simulation-based feedback mechanisms to enhance the planning and decision-making capabilities of autonomous vehicles. Similarly, Raquel Urtasun's team integrates perception, prediction, and planning within a closed-loop system utilizing large-scale neural networks. By leveraging continuous data feedback for optimizing scenario perception and behavior prediction, and

Table 10.23 Countries/regions with the greatest output of core patents on “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”

No.	Country/regions	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	41	75.93	653	73.79	15.93
2	China	5	9.26	201	22.71	40.20
3	Japan	5	9.26	56	6.33	11.20
4	Republic of Korea	2	3.70	31	3.50	15.50
5	Cayman Islands	2	3.70	2	0.23	1.00
6	UK	1	1.85	21	2.37	21.00
7	Israel	1	1.85	18	2.03	18.00
8	Germany	1	1.85	2	0.23	2.00

employing technologies such as generative adversarial networks (GANs), their system has significantly improved robustness across various environments, particularly in complex urban contexts. DeepMind has effectively incorporated large language models into decision-making systems in autonomous driving, particularly in multimodal learning and scenario interpretation. By merging language models with vision and perception models, autonomous driving systems are able to extract semantic information from extensive scenario data and offer decision-making recommendations in a manner that is interpretable to human users. Additionally, the Meta AI team has created a method to automatically generate textual descriptions of driving scenarios using large language models. By integrating these descriptions with scenario libraries, they have enhanced the system's scene understanding and response speed. The top three institutions leading in core patents within this domain are Baidu, PlusAI, and Google (Table 10.24). According to the collaboration network of major institutions producing core papers (Figure 10.17), Baidu has established substantial partnerships with Apollo Intelligent Driving Technology (Beijing) Co., Ltd.

Looking ahead, the advancement of “development of large model technologies and scenario libraries for closed-loop data in autonomous driving” will be propelled by the necessity to enhance multisource data fusion capabilities and improve predictive accuracy in complex scenarios. Key technologies such as natural language processing and multimodal scenario recognition will be leveraged to foster diversity, reliability, and safety. Figure 10.18 illustrates the roadmap of this front.

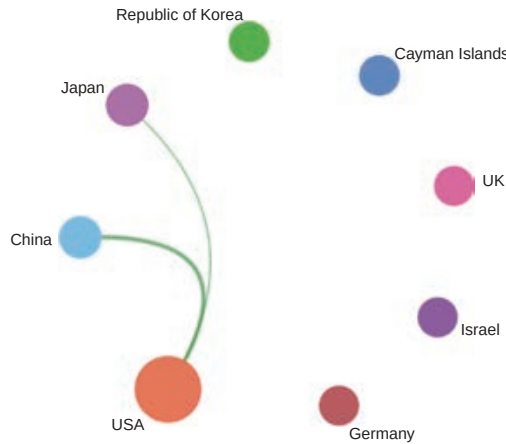


Figure 10.16 Collaboration network among major countries/regions in the engineering development front of “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”

Table 10.24 Institutions with the greatest output of core patents on “development of large model technologies and scenario libraries for closed-loop data in autonomous driving”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Baidu Online Network Technology (Beijing) Co., Ltd.	15	27.78	416	47.01	27.73
2	PlusAI, Inc.	8	14.81	127	14.35	15.88
3	Google, Inc.	5	9.26	58	6.55	11.60
4	Toyota Motor Company	4	7.41	68	7.68	17.00
5	Tesla, Inc.	2	3.70	28	3.16	14.00
6	TuSimple, Inc.	2	3.70	3	0.34	1.50
7	Pony.ai, Inc.	2	3.70	2	0.23	1.00
8	Apollo Intelligent Driving Technology (Beijing) Co., Ltd.	1	1.85	120	13.56	120.00
9	NVIDIA Corporation	1	1.85	39	4.41	39.00
10	LG Electronics Inc.	1	1.85	26	2.94	26.00

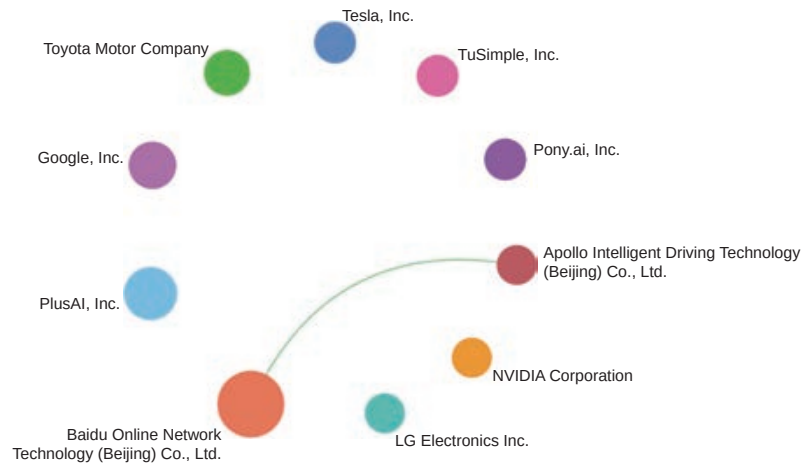


Figure 10.17 Collaboration network among major institutions in the engineering development front of "development of large model technologies and scenario libraries for closed-loop data in autonomous driving"

Milestones	Sub-milestones	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Goals	Build an interconnected, efficient, intelligent, and safe autonomous vehicle system	Promote autonomous driving applications primarily based on autonomous environmental perception supplemented by connected information services	Develop networked environmental perception capabilities to enable conditional autonomous driving applications in complex conditions				Advance intelligent technologies capable of V2X cooperative control and highly/fully autonomous driving				
							Achieve full coordination with transportation, information, and internet sectors, deeply integrating with intelligent transportation and smart city industries				
Requirements		Systematically enhance the perception and fusion of multi-source heterogeneous data, optimize the data imbalance issue, and achieve a highly reliable and safe data perception process									
		Fully improve predictive capabilities in complex dynamic scenarios, providing effective solutions for diverseroad conditions, unpredictable traffic behavior, and complex environmental variables									
		Strengthen the prediction capability for extreme rare long-tail scenarios, overcome estimation biases caused by scarce dala, and ensure comprehensive coverage in scenario generation and testing									
Key directions	Multimodal data fusion and scenario generation	Research on multimodal data fusion technology covering complex road conditions, weather, and pedestrian behavior				Research on multimodal complex driving scenario generation, simulation, and testing based on prompt learning and context awareness			Research on dynamic adjustment and optimization of automatic prompt generation technology for specific scenario needs		
	Long-tail scenario prediction and data closed-loop system	Research on learning and prediction technologies for extreme rare safety-critical events with high generalization and reasoning capabilities				Rescarch on optimization strategies for dynamic scenario generation with high robustness and adaptability			Research on building a sustainable data optimization closed-loop system for autonomous driving scenario generation and testing		
Key technologies	Perception module	MVX-Net, PFF3D, and other early fusion technologies; ContFuse, EPNet, and other deep fusion technologies; CLOCs and other late fusion technologies; MV3D, MLOD, and other asymmetric fusion technologies; F-ConvNet, Faraway-Frustum, and other weak fusion technologies					Multimodal Transformer scene recognition and natural language generation technology				
							Large language model data fusion framework based on multimodal feature alignment and correlation				
	Planning module	Global path planning algorithms such as Dijkstra, A*, RPT; local path planning algorithms such as DWA; motion planning algorithms such as Bezier curves, multi-objective optimization, and MPC					Path and behavior planning based on natural language understanding and reasoning				
							Real-time dynamic path optimization algorithm based on multi-task learning decomposition				
	Decision module	Behavior decision algorithms such as FSM, MDP, and RL					Complex scenario decision-making based on contextual learning, chain of thought, and reinforcement learning				
Control module	Control algorithms such as PID, MPC, LQR, SMC, imitation learning, and deep reinforcement learning					High-precision control instruction generation technology based on natural language					

Figure 10.18 Roadmap of the engineering development front of "development of large model technologies and scenario libraries for closed-loop data in autonomous driving"

10.2.2.3 Cloud-edge-end data collaborative management platform for engineering construction

The cloud-edge-end data collaborative management platform for engineering construction represents an intelligent system for managing construction data, designed within a collaborative architecture that spans cloud, edge, and terminal nodes. By real-time and comprehensive data collection from all stakeholders in the construction process, the platform enables in-depth analysis of the knowledge and value embedded in the data. This capability facilitates more accurate and timely oversight of project progress, resource allocation, and quality risk management. Current research in this area focuses on the following key aspects:

(1) Cloud-edge-end node management technology for engineering construction

Cloud-edge-end node management technology ensures timely data processing through dynamic resource scheduling at cloud and edge nodes, coupled with real-time monitoring and access control at terminal nodes. By applying evolutionary game theory and coordination mechanisms among system components, incentive mechanisms are utilized to optimize resource allocation and task scheduling. This approach promotes an optimal balance of performance and efficiency across nodes, thus enhancing resource utilization during the construction process. Key research topics include node access control and the coordination mechanisms informed by evolutionary game theory among system components.

(2) Edge-terminal and cloud-edge collaborative technologies for engineering construction

Edge-terminal collaboration technology in engineering construction facilitates efficient collaboration and low-latency control between terminal devices and edge computing nodes. This is achieved through real-time data collection and transmission, data synchronization and feedback, dynamic task allocation, and data security protection. Cloud-edge collaboration technology enhances data processing efficiency and system optimization via dynamic task allocation and load balancing, data synchronization and transmission, edge caching and preprocessing, collaborative scheduling and resource management, as well as real-time feedback and control. Ultimately, this technology enables global resource optimization and intelligent decision support. Key research areas in this field include edge-terminal node computational collaboration, cloud-edge task collaboration, and synchronized data transmission and distribution.

(3) Cloud-edge data analysis and algorithm optimization in engineering construction

The cloud-edge data analysis and algorithm optimization technology in engineering construction aims to leverage advanced data mining and machine learning algorithms to enhance the precision and speed of collaborative data processing on the cloud-edge-end platform. Through in-depth analysis of extensive engineering data, key features and trends are identified to inform engineering decisions. Continuous algorithm optimization ensures real-time and accurate collaborative data processing, supporting the dynamic analysis and management of data across all parties involved in the platform. This approach guarantees the optimal utilization of data resources during construction, thereby improving overall project efficiency and quality. Key research topics in this area include the development of data mining and analysis algorithms, multi-source heterogeneous data fusion and analysis, and data quality assessment and optimization.

(4) Cloud-edge computing task offloading strategies and optimization in engineering construction

Cloud-edge computing task offloading strategies in engineering construction dynamically allocate tasks to either cloud or edge nodes based on their computational requirements and resource consumption. This approach ensures efficient execution of computational tasks while minimizing system response times through effective load balancing. The dynamic optimization of these strategies enhances the intelligence of task offloading, facilitating optimal allocation and full utilization of computing resources. By implementing real-time monitoring and feedback mechanisms, the cloud-edge-end platform can adjust task offloading strategies to adapt to evolving project demands, ensuring flexible and responsive data management throughout the construction process. Key research areas in this domain include the optimization of computing task scheduling and offloading strategies, load balancing, resource allocation optimization, and the implementation of real-time monitoring and dynamic feedback mechanisms.

(5) Cloud-edge-end and blockchain integration technology in engineering construction

Cloud-edge-end and blockchain integration technology combines cloud-edge-end architecture with blockchain to address security and trust concerns related to data storage, computation, transmission, and system management. The primary research directions in this field include: utilizing blockchain's multi-replica storage mechanism to ensure data integrity; employing blockchain smart contracts to establish a trusted computing framework for the cloud-edge-end system; leveraging blockchain consensus mechanisms for trusted data sharing among system participants; and applying blockchain's chain structure and hash encryption for data traceability. However, the integration of cloud-edge-end architecture with blockchain faces several challenges. For example, the heterogeneity of nodes at various levels of the cloud-edge-end architecture may conflict with the peer-to-peer nature of nodes in blockchain networks. Additionally, single-point failures within the cloud-edge-end blockchain system could result in the leakage of replicated data, raising significant privacy concerns for users. Furthermore, blockchain consensus mechanisms and smart contracts can increase both storage and computational costs at edge nodes. Addressing these challenges will be a critical focus for future research and development in cloud-edge-end blockchain integration technology.

In terms of patent numbers, China leads with the highest number of patent disclosures, accounting for 66.67%, while Japan boasts the highest citations per patent (Table 10.25). Currently, there is no established collaboration among major countries. The leading institutions for patent disclosures are the State Grid Corporation of China and Zhongke Fanyu (Wuhan) Technology Co., Ltd. (Table 10.26), and there are presently no collaborations between these institutions.

Looking ahead, the development of the cloud-edge-end data collaborative management platform for engineering construction is poised to advance toward more precise analytics, increased collaboration efficiency, and heightened data security. The emergence of large AI models will empower the platform with sophisticated data analysis capabilities, enabling more autonomous predictions and decision-making support based on data insights. Enhancements in terminal data collection and the computational power of edge devices will further optimize data transmission and resource utilization throughout the platform. Furthermore, the integration of blockchain technology with the cloud-edge-end architecture is set to safeguard data privacy and bolster security, thus providing a solid foundation for the platform's reliability and safety. Figure 10.19 shows the roadmap of "cloud-edge-end data collaborative management platform for engineering construction".

Table 10.25 Countries with the greatest output of core patents on "cloud-edge-end data collaborative management platform for engineering construction"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	28	66.67	15	22.39	0.54
2	Japan	5	11.90	30	44.78	6.00
3	USA	3	7.14	6	8.96	2.00
4	Republic of Korea	3	7.14	1	1.49	0.33
5	UK	1	2.38	15	22.39	15.00
6	Germany	1	2.38	0	0.00	0.00
7	France	1	2.38	0	0.00	0.00

Table 10.26 Institutions with the greatest output of core patents on “cloud-edge-end data collaborative management platform for engineering construction”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	State Grid Corporation of China	3	7.14	0	0.00	0.00
2	Zhongke Fanyu (Wuhan) Technology Co., Ltd.	3	7.14	0	0.00	0.00
3	Mitsubishi Electric Corporation	2	4.76	2	2.99	1.00
4	Toshiba Corporation	1	2.38	26	38.81	26.00
5	British Telecommunications	1	2.38	15	22.39	15.00
6	Shandong Gelinban Building Materials Technology Co., Ltd.	1	2.38	7	10.45	7.00
7	Novartis AG	1	2.38	3	4.48	3.00
8	Beijing Zhiyi Yangfang Technology Co., Ltd.	1	2.38	2	2.99	2.00
9	Guangdong Taiyi High-tech Development Co., Ltd.	1	2.38	2	2.99	2.00
10	Informatix, Inc.	1	2.38	2	2.99	2.00
11	Newman Cloud, Inc.	1	2.38	2	2.99	2.00

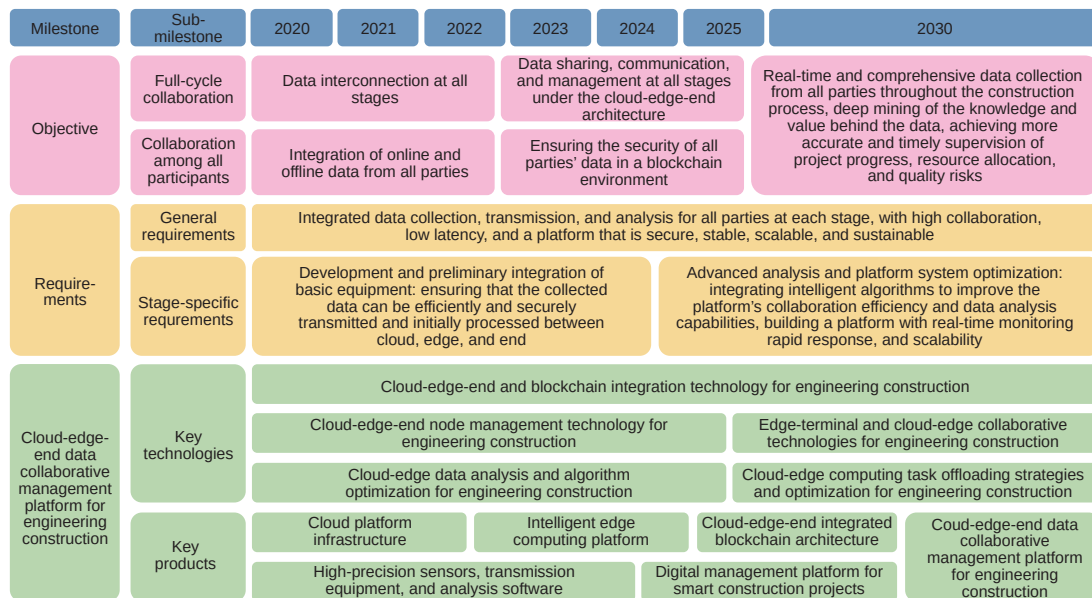


Figure 10.19 Roadmap of the engineering development front of “cloud-edge-end data collaborative management platform for engineering construction”

10.2.2.4 Emotionally and intellectually capable digital humans for service innovation

The essence of emotionally and intellectually capable digital humans resides in their ability to simulate human emotions and intelligence, allowing machines to engage in more natural and empathetic interactions. As a cutting-edge technology within the domain of artificial intelligence, this field is gaining prominence in both scientific research and industrial applications.

It includes not only AI, human-computer interaction, and virtual reality technologies but also emerging disciplines such as affective computing. The objective is to develop intelligent agents that can understand, learn, and adapt to complex social environments.

Emotionally and intellectually capable digital humans hold considerable promise across various domains. In the mental health sector, they can detect and evaluate cognitive abilities and emotional states, providing personalized companionship, support, and interventions. In education, they can tailor teaching strategies based on students' emotional conditions, thereby enhancing learning effectiveness. In the service industry, they can enrich user experiences and streamline problem-solving processes. In entertainment, they can deliver more diverse and customizable experiences, such as virtual idols and virtual hosts.

The development of digital human technology has progressed from basic graphical modeling and rendering to sophisticated emotional interactions. In its formative years, digital humans primarily manifested in cartoonish or simplified representations, with behaviors and movements derived from pre-defined databases and largely depicted in two-dimensional formats. Advancements in graphics technology have facilitated detailed modeling and rendering, particularly in the ultra-fine representation and control of features such as skin, hair, and facial details, resulting in highly realistic digital humans. Concurrently, progress in artificial intelligence has propelled innovations in the automatic generation of digital human images and movements.

At present, digital human technology can achieve highly realistic simulations of appearance and movement; however, there remains significant potential for improvement in emotional expression and interaction. The primary challenge lies in the fundamental principles of human cognition and psychological science, areas for which relevant theories and key technologies are still developing. As AI technology continues to evolve, future digital humans will increasingly focus on simulating and expressing emotions.

Emotionally and intellectually competent digital humans represent advanced forms of virtual digital humans, involving research areas related to both appearance modeling, motion driving, speech synthesis, and realistic rendering, as well as key domains associated with “emotion” and “intelligence”. In the context of “emotion”, current research primarily addresses emotional modeling, emotional perception, emotional encoding, and emotional expression. Emotional modeling serves as the foundation for constructing the emotional states of digital humans, whereas emotional perception involves the capture of human emotional signals through various sensors. Emotional encoding translates perceived emotional information into processable data, and emotional expression pertains to how digital humans communicate emotions through language, facial expressions, and gestures. For “intelligence”, current research concentrates on the intelligent understanding of the environment, decision-making, feedback mechanisms, and the ability of digital humans to learn and adapt over time.

Research on emotionally and intellectually capable digital humans spans multiple countries. As illustrated in Table 10.27, China significantly outpaces other nations in this field. Leading institutions include universities, research institutes, and high-tech companies, particularly those with robust innovation capabilities, such as Shenzhen Zhuiyi Technology Co., Ltd., Industrial and Commercial Bank of China, and China Construction Bank (Table 10.28). The interdisciplinary nature of digital human research necessitates collaboration among scientists and engineers from various fields, including artificial intelligence, cognitive psychology, and artistic design.

Table 10.27 Countries with the greatest output of core patents on “emotionally and intellectually capable digital humans for service innovation”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	50	92.59	57	100.00	1.14
2	Republic of Korea	3	5.56	0	0.00	0.00
3	India	1	1.85	0	0.00	0.00

Collaboration among major countries remains limited, indicating that major countries have independently achieved mastery over all technological components, allowing for comprehensive research and development within their national borders. The sole example of institutional collaboration has been between Shanghai Movai Technology Co., Ltd. and Xmov (Shanghai) Information Technology Co., Ltd. (Figure 10.20).

Figure 10.21 presents the roadmap of “emotionally and intellectually capable digital humans for service innovation”. This technology is contingent upon advancements in artificial intelligence and has recently concentrated on four primary areas: high-precision human modeling and animation, multimodal interaction, affective computing, and autonomous learning and decision-making. Future developments will prioritize high-precision human modeling, large-model-driven behavior generation, proactive interaction informed by situational awareness, emotional encoding and generation, and autonomous learning and decision-making powered by large models. This technology holds expansive applications in service sectors such as cultural tourism, healthcare, and government services.

Table 10.28 Institutions with the greatest output of core patents on “emotionally and intellectually capable digital humans for service innovation”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Shenzhen Zhuiyi Technology Co., Ltd.	6	11.11	5	8.77	0.83
2	Industrial and Commercial Bank of China	4	7.41	9	15.79	2.25
3	China Construction Bank Corporation	3	5.56	7	12.28	2.33
4	Beijing Baidu Netcom Science and Technology Co., Ltd.	2	3.70	1	1.75	0.50
5	Beijing Welink Technology Co., Ltd.	2	3.70	1	1.75	0.50
6	4U (Beijing) Technology Co., Ltd.	2	3.70	0	0.00	0.00
7	Guangzhou Bairui Network Technology Co., Ltd.	2	3.70	0	0.00	0.00
8	Tricometek Co., Ltd.	2	3.70	0	0.00	0.00
9	Shanghai Movai Technology Co., Ltd.	1	1.85	6	10.53	6.00
10	Xmov (Shanghai) Information Technology Co., Ltd.	1	1.85	6	10.53	6.00

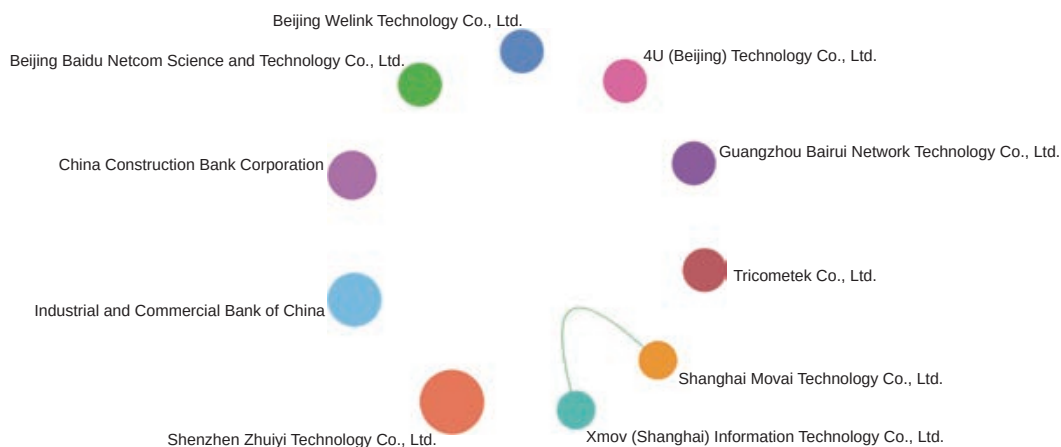


Figure 10.20 Collaboration network among major institutions in the engineering development front of “emotionally and intellectually capable digital humans for service innovation”

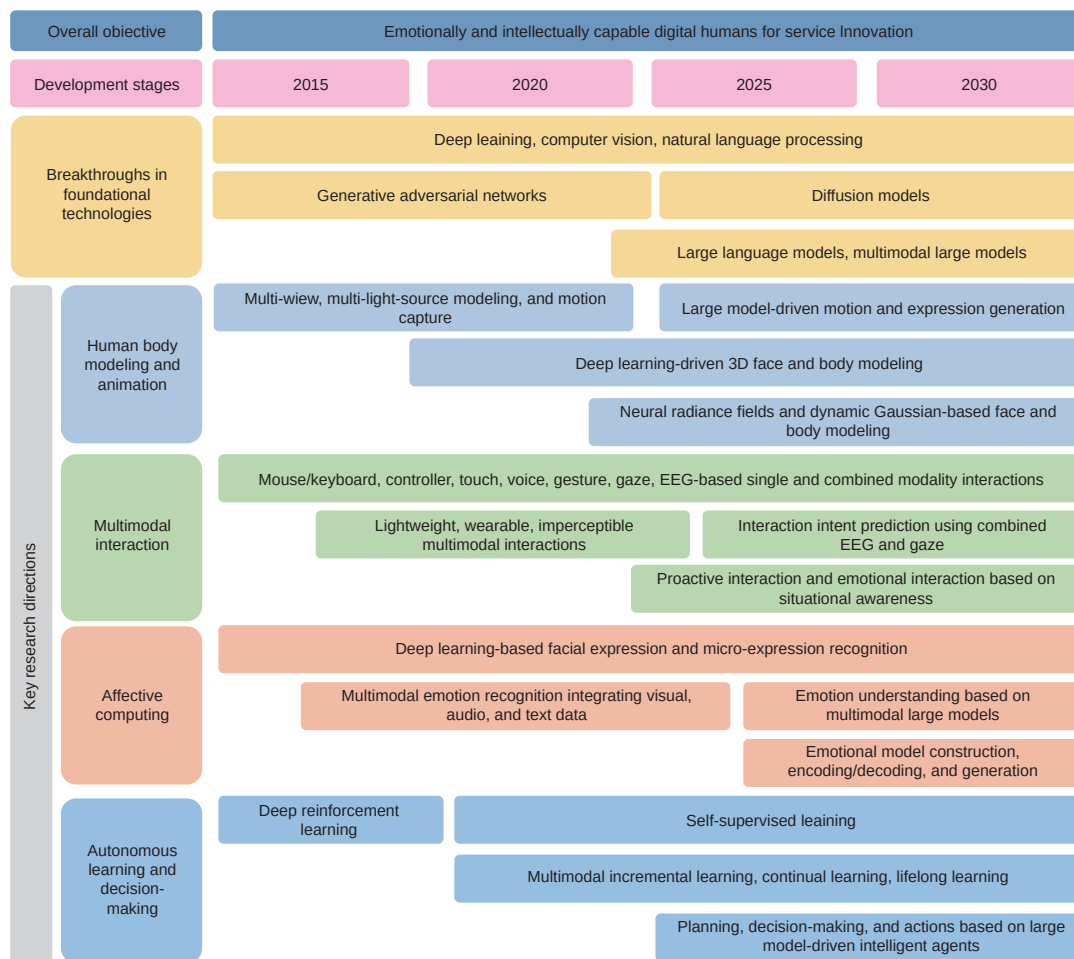


Figure 10.21 Roadmap of the engineering development front of “emotionally and intellectually capable digital humans for service innovation”

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